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Technical aspects of spiral CT

Spiral CT allows fast and continuous acquisition of data from a complete volume.

A spiral CT scanner is a CT device which can not only make a conventional, or slice-to-slice scan, but can also perform a scan in which the patient moves slowly through the gantry, while the X-ray tube and detector rotate in a plane perpendicular to the major axis of the patient. This means that the X-ray tube and detector perform a 'spiral' or 'helical' movement with respect to the patient, generally at a rate of one revolution per second. This technique allows fast and continuous acquisition of the data from a complete volume. Many coarse data sets, each of one rotation, are created by interpolation of the spiral data, after which the axial images are generated using the standard reconstruction techniques.

A complete data set can be acquired in a single breathhold.

The advantages of speed and continuity can be seen in applications such as imaging of the lungs. The speed allows the complete data set to be acquired within one breathhold. This avoids the problem of parts of the lung being missed because the patient breathes differently in consecutive acquisitions.

Blood vessels can be imaged at maximum opacification.

The speed of acquisition also makes it possible to make better use of the contrast dynamics of intravenously administered contrast agents, e.g. in CT angiography (CTA). This allows blood vessels to be imaged while they contain the maximum amount of contrast agent. It is also possible to obtain images of a complete organ in one or several specific phases of contrast enhancement, by scanning the volume repeatedly during a single contrast cycle. In the latter case the scans are referred to as multiphasic scans, and are used in such applications as the detection and classification of liver tumours.

The speed and continuity of acquisition in spiral CT also has certain disadvantages. Due to the high speed, the quantity of radiation generated per rotation is smaller, resulting in reduced image quality. Due to the continuity of the movement, every measurement is done in a slightly different part of the anatomy. This results in increased slice thickness and, in some applications, the presence of artifacts.

The basic principles of conventional and spiral CT have been extensively described in the literature [1–8]. This review describes those parameters that affect the quality of a spiral CT data set, and the way in which they should be selected in order to optimize the diagnostic quality of the scan.

Spatial resolution

Spatial resolution is a measure of how well a detail is delineated in an image. The spatial resolution in the scan plane is referred to as the axial spatial resolution. Resolution in the coordinate perpendicular to the scan plane, i.e. in the z-direction, is referred to as the longitudinal spatial resolution.

Axial spatial resolution

The axial spatial resolution is principally determined by the distances between the X-ray tube, the centre of rotation, and the detector, as well as by the width of the focus and the detector elements, and the number of measurements made per rotation. These factors are determined by the construction of the scanner.

CT protocols generally allow the resolution to be increased by selecting a sharper reconstruction filter and high-resolution reconstruction. However, the latter facility is not available in spiral CT, due to the difference in the use of 'extra' data. The standard axial resolution requires the data from slightly more than a half-rotation (180° + fan angle). If the data from a complete rotation are available, the extra

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data can be used in one of two ways. They can be used to increase the spatial resolution by 'interweaving' the views, in order to obtain 'high-resolution' scans, or they can be used to reduce the effect of movement, which is what is done in spiral CT.

Longitudinal spatial resolution

The longitudinal spatial resolution is principally determined by the selected protocol. It is described by the 'slice-sensitivity profile' (SSP) (Fig. 1). This curve shows the relative contribution of the anatomy along the z-axis to the reconstructed image. In conventional CT, the longitudinal spatial resolution is entirely determined by the slice thickness. In spiral CT, the longitudinal resolution is also determined by the table increment per rotation, and by the interpolation algorithm used.

Collimation or slice thickness

The width of the X-ray beam is determined by collimators mounted in front of the X-ray tube. Geometric effects (distance between X-ray tube, centre of rotation and detector; height of the focus; position and setting of the collimator) lead to a more-or-less gradual increase and decrease of the quantity of radiation around the edges of the slice. In conventional scanning, the SSP and the dose profile coincide precisely. The width of this profile, measured at half the maximum level (full width at half maximum, FWHM) is then the collimated slice thickness or, in other words, the collimation.

Table increment, pitch

In spiral CT, the table increment per rotation can be selected independently of the selected slice thickness. A larger table increment gives faster acquisition, but leads to a wider SSP and, consequently, lower resolution. The relationship between table increment per rotation and slice thickness is referred to as 'pitch'. The table increment is typically from one to two times the size of the selected collimation (pitch 1–2). The spatial resolution with 5 mm collimation and a table increment of 7 mm (pitch 1.4) lies between that of 5 mm collimation with pitch 1, and 7 mm collimation with pitch 1.

The longitudinal resolution is principally determined by the selected protocol.

Interpolation algorithm

One reconstructed image uses the data from at least one rotation. Because the patient is moved during the acquisition, the information obtained varies over a volume corresponding to the slice thickness plus the table increment per rotation. This data inconsistency causes artifacts. This can, to some extent, be compensated by interpolating the acquired data. The methods most commonly used are the 180° and the 360° interpolation algorithms. The 180° interpolation algorithm uses the data from one rotation. The data obtained with a half-rotation difference is interpolated within one rotation. In the 360° interpolation, two complete rotations are used. Data acquired with a difference of a complete rotation are then interpolated in the reconstruction. The disadvantage of 360° interpolation is a significant increase in the width of the SSP and, consequently, a reduction in the longitudinal resolution. The FWHM of the SSP increases by 30 % at pitch 1. In 180° interpolation there is also a change in the SSP, but the FWHM at pitch 1 remains constant. For this reason, the 180° interpolation algorithm is generally preferred, and is often implemented as standard. A disadvantage is that artifacts due to data inconsistency remain more severe (see section on *Spiral artifacts* below), and the noise increases with 8 % compared to conventional scans (9).

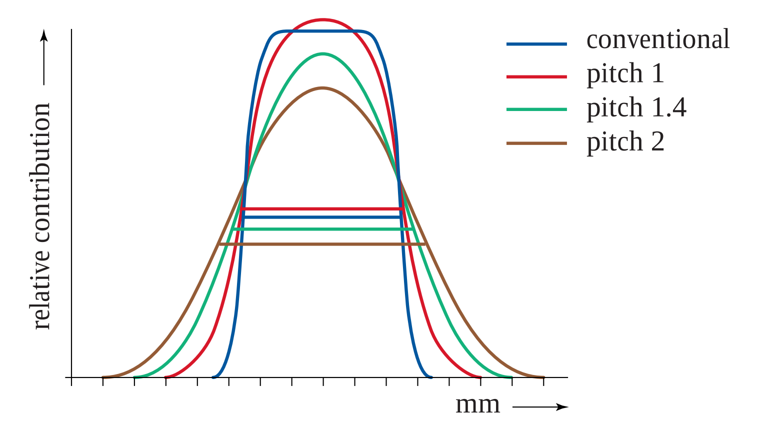

Fig. 1. Slice sensitivity profiles (SSPs) for conventional and spiral acquisitions, with 5 mm collimation. The horizontal lines indicate the corresponding FWHM. The FWHM values increase with increasing pitch. The steep edges of the conventional scan indicate that the boundaries of the slice are sharply defined: a small structure is either within the slice, contributing fully to the image, or outside the slice, not contributing at all to the image. For spiral acquisition the edges become less steep. This means that structures outside the nominal slice thickness contribute to some extent to the image. This effect is larger with increasing pitches, but is not shown by the FWHM values. The significance of these FWHM values is therefore limited.

The 180° interpolation algorithm is used in the rest of this article, as well as in the Figures.

Effective slice thickness
The total effect of the collimation, pitch and interpolation is described by SSP. The FWHM of this curve is often used as a measure for what is denoted the 'effective slice thickness'. With the 180° interpolation the FWHM of a pitch 1 acquisition is similar to that of a conventional scan with the same collimation. For larger pitches the FWHM increases linear up to about 30 % at pitch 2. However, this measure is of limited value. Comparing a conventional scan with a pitch 1 acquisition with the same collimation, the FWHM of both SSP's are approximately the same. While the SSP of the conventional scan has a very steep edges, the SSP of the spiral scan is more bell shaped. This means that in the latter case the area of anatomy that contributes to the image is wider. Although the structures in the edges do not contribute fully, high contrast details will contribute to the image. This effect increases with increased pitch (Fig 1).

Reconstruction index
The reconstruction index in spiral CT is comparable to the table index in conventional CT. It indicates the distance between consecutive slices, without affecting the slice thickness. The advantage of a small index is that it gives a greater chance of optimum visualization of a given detail. The reconstruction index in spiral CT can be selected without affecting the acquisition time or the dose used. Two to three reconstructions per rotation are generally selected as standard [10].

Interpolation can cause artifacts in conical structures.

Combined effects of resolution and imaged structure

Insufficient axial and longitudinal resolution can cause partial volume effects and spiral artifacts.

Every axial image shows the effects of both the axial and the longitudinal resolution on the structures shown. These are the partial volume effect, and spiral artifacts.

Partial volume effect
In a CT scan, every part of the patient is represented by a pixel in a reconstructed image. If the slice is relatively thick, each pixel in the CT image will represent a larger quantity of tissue. If this quantity of tissue has different components, e.g. kidney parenchyma and fat, the pixel will be allocated a Hounsfield number somewhere between those of the two types of tissue. Consequently, the outlines of structures in the scan will appear to be vague, while this may not really be the case. The effect is most marked when structures vary in shape or position along the patient's longitudinal axis. Because spiral CT increases the width of the SSP, the partial volume effect will also increase.

Spiral artifacts
The interpolation algorithm is meant to overcome artifacts due to data inconsistency. This is only successful to some extent. The remaining effects can be divided in two groups. Many artifacts are a combination of both effects.

Cone artifacts
Imagine a spiral scan of a cone. Towards the top of the cone the diameter decreases. Thus, the successive projections or profiles the CT scanner makes, register a declining diameter of the cone. These projections each get their own weighting factor in the interpolation process, after which reconstruction follows. The interpolation scheme does not treat every projection in the same way. This implies that in some directions the profiles are averaged with the profiles acquired half a rotation further, while in other directions the opposite profiles are not used at all. This gives an effect in the image similar to partial volume averaging where in one direction the partial volume averaging is determined by the collimation only, while in another direction by the collimation as well as the table increment per rotation. Instead of a perfect circle, we see an ellipse-like reconstruction. The artifacts are more apparent when the cone has a large top angle, or when large pitches are used. In a patient we can see this effect, for example, in spiral scans of the top of the brain. The inclining surface of the skull leads to artifacts. The artifacts can be seen as two crescent shaped bands of increased density along the skull-brain interface, mimicking subdural haematoma (Fig. 2). When three or more reconstructions per rotation are made, these bands rotate around the brain in the same direction as the X-ray tube rotated around the patient.

Rod artifacts
Imagine a spiral scan of a cylinder or rod, angulated with respect to the scan plane. The table

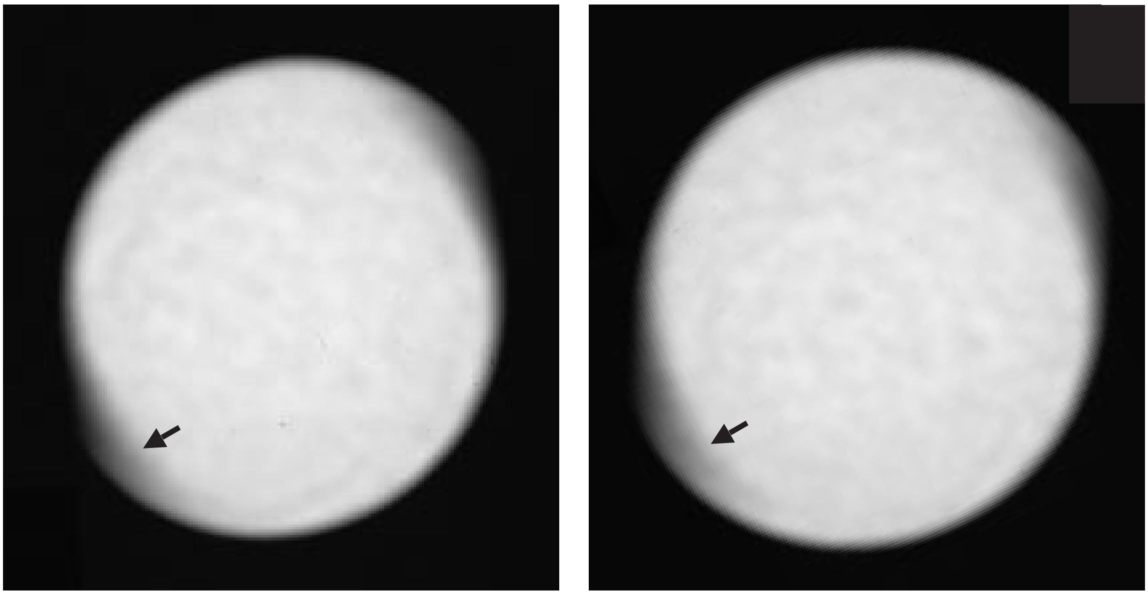

Fig. 2 a. Spiral scans of a cone, scanned with 5 mm slice thickness and pitch 2. Arrows indicate the cone artifacts.

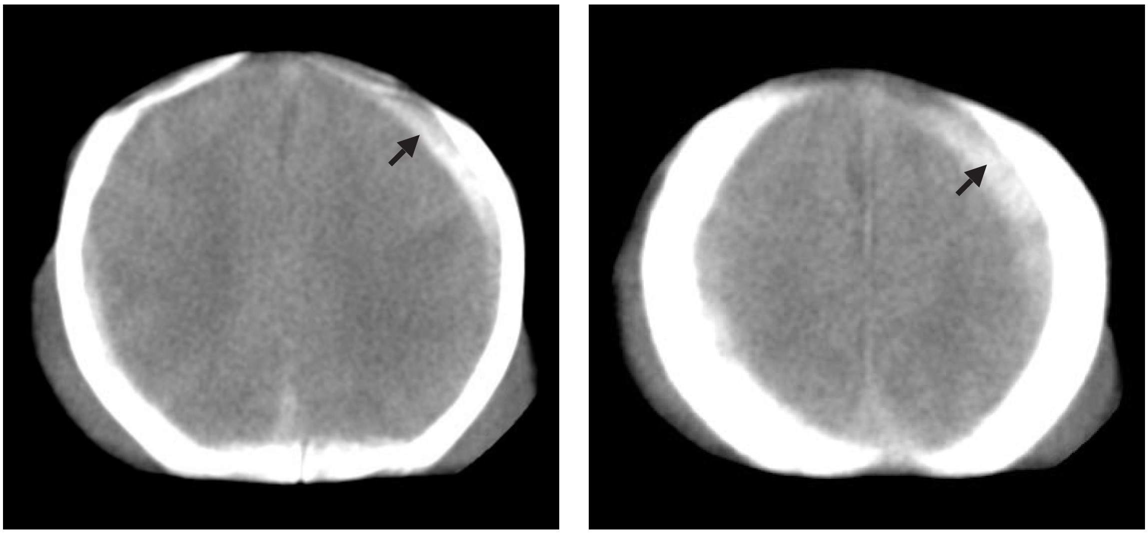

Fig. 2 b. Cone artifacts in the skull of a newborn, scanned with 10 mm slice thickness, pitch 1. The artifacts get more severe towards the top of the skull (arrows).

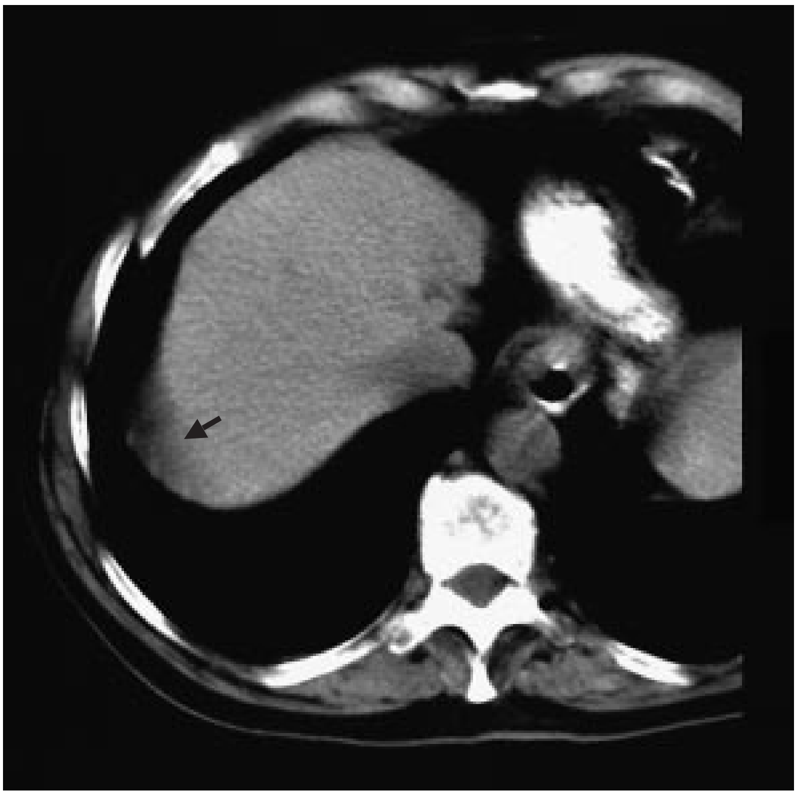

Fig. 2 c. Cone artifacts in the liver (arrows). Scan protocol: 5 mm slice thickness, pitch 2.

Fig. 3 a.
Spiral scans of a rod scanned in air. The rod is 1 cm in diameter, and angulated at 45° with respect to the scan plane. Slice thickness 5 mm, pitch 2. The rod should appear as an ellipse in the scan plane, but its image is distorted. There are also apparent Hounsfield shifts in the surrounding air.

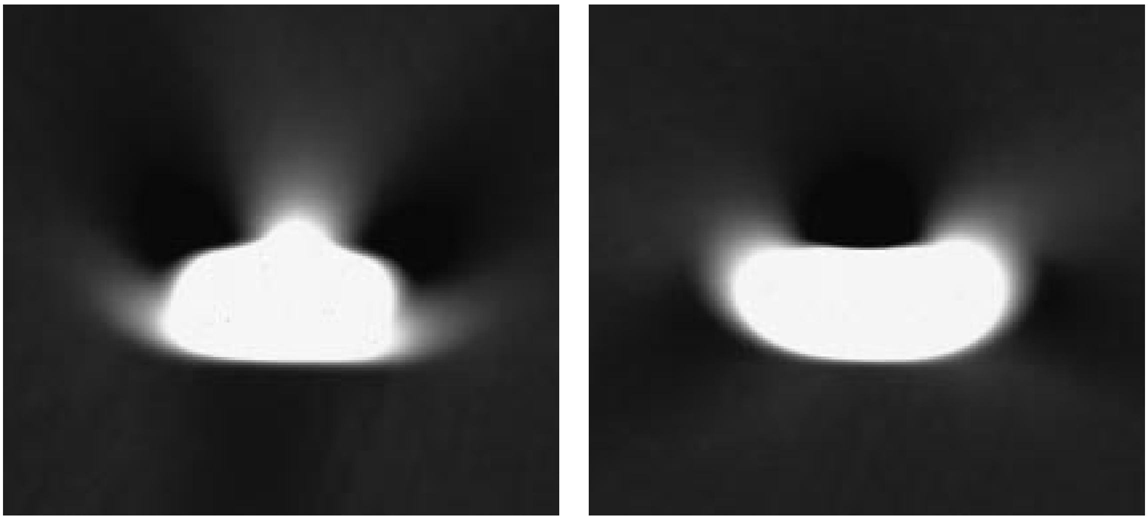

Fig. 3 b.
Spiral scan of the cadaver of a 90 year old female. Slice thickness 5 mm, pitch 2. There are rod artifacts in the liver (arrows).

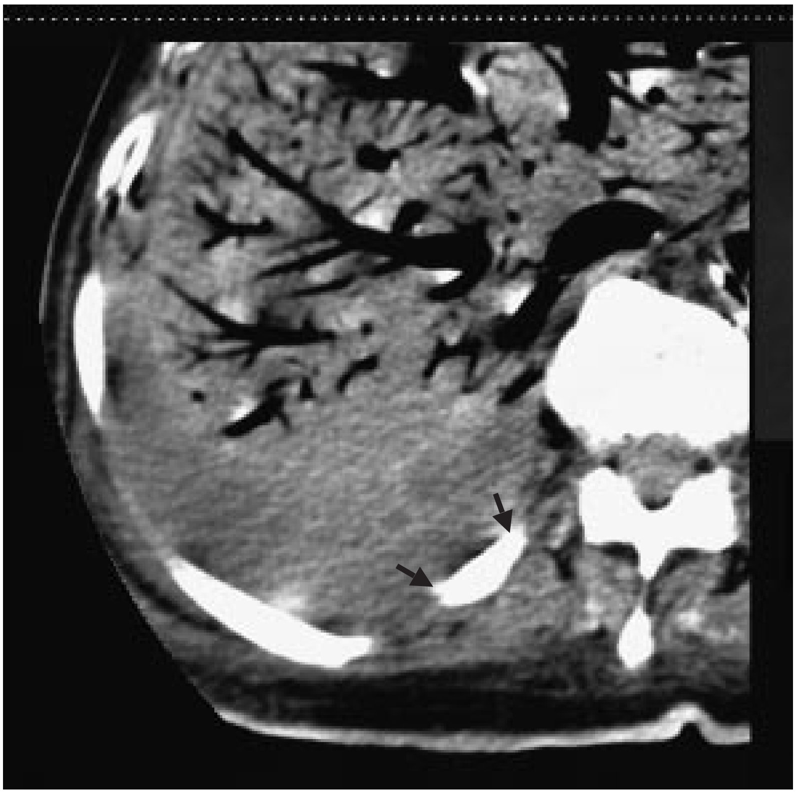

Table increment can distort the image of cylindrical structures.

with the rod is moved during acquisition, thus the position of the rod in the scan plane changes. Every subsequent projection locates the rod at a different position. Without table movement, i.e. in a conventional scan, the image would show an ellipse. With table movement, the variation in the registered position of the rod, together with the interpolation scheme, gives a distortion of the ellipse like form with Hounsfield shifts in the surrounding tissues. These artifacts are especially seen in the liver in the area of the ribs (Fig. 3).

Spiral artifacts are apparent when high contrast objects vary in shape and/or position in an area where we are interested in low-contrast morphology. Besides the already mentioned areas, we have to be aware of these artifacts e.g. in the upper dome of the liver, the bowel and in CTA. In the liver they are caused by the interface with the lung tissue, in the bowel wall we get artifacts from the bowel gas. In CTA Hounsfield changes may simulate stenotic parts in blood vessels. All artifacts increase with increased pitch.

Contrast resolution

In order to make a CT scan, a quantity of radiation is required. The more radiation it is possible to detect, the better the signal-to-noise (S/R) ratio will be, improving the visibility of details of a given size and contrast. Contrast resolution indicates the details that are just

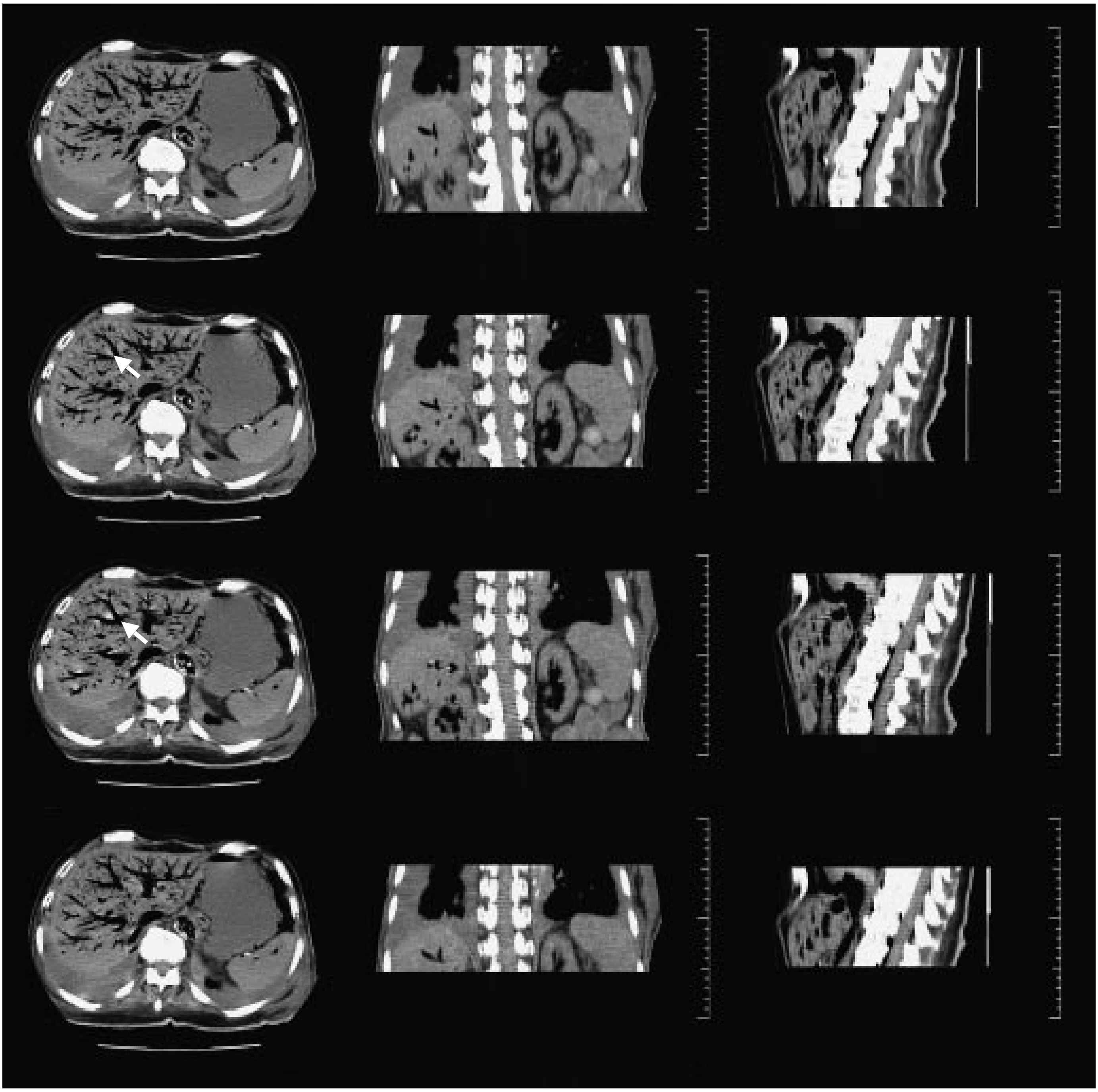

Fig. 4. Scans of the cadaver of a 90 year old female.
Top row: conventional scan, scan parameters: slice thickness 5 mm, table increment 5 mm, 120 kV, 300 mAs.
Second row: spiral scan, scan parameters: slice 5 mm, table movement 5 mm per rotation (pitch 1), reconstruction index 1 mm, 120 kV, 300 mAs.
Third row: spiral scan, scan parameters: slice thickness 5 mm, table movement 7 mm per rotation (pitch 1.4), reconstruction index 1 mm, 120 kV, 300 mAs.
Bottom row: spiral scan, scan parameters: slice thickness 7 mm, table movement 7 mm per rotation (pitch 1), reconstruction index 1 mm, 120 kV, 225 mAs.
The scan parameters are selected such that the noise in all axial images is similar. The patient dose for the first, second and fourth row is about the same.
The left-hand column shows the axial images, the middle column shows coronal curved multi-planar reconstructions (MPRs) through the spinal cord, and the right-hand column shows sagittal curved MPRs through the spinal cord.
Comparing the axial spiral scans to the conventional scan, we see density changes around high contrast structures, which are not present at the conventional scan (arrows). These changes are spiral artifacts.
In the MPRs of the conventional scans we see stairstep artifacts, due to the table increment between the scans. These are best seen in and around the left kidney and the vertebrae.
In the MPRs of the spiral data sets these have vanished. This is due to the small reconstruction index used. Instead we find small 'feathers' in soft tissue, around high contrast details, especially in the spinal cord and around the ribs.
These are spiral artifacts. Comparing pitch 1.4 acquisition (3rd row) with the pitch 1 acquisition (2nd row) we find an increase in amplitude and a decrease in frequency.
The frequency is inversely proportional to the table increment per rotation.
The 5 mm slice thickness with pitch 1 gives the best longitudinal resolution.

visible at a given X-ray dose. A typical value is that, at 40 mGy, details with a diameter of 3 mm and a contrast of 3 H are just visible. Spiral CT requires a sequence of several rotations one after the other. This means that the X-ray tube is under load for a longer time. Consequently, the maximum permissible tube current in spiral CT is less than that in conventional CT. Thus, the dose is lower, and in most protocols for spiral CT the contrast resolution is less than that obtained with conventional protocols. Even with comparable scan parameters, the contrast resolution in spiral CT will be slightly less than that in conventional CT. This is due on one hand to the interpolation algorithm, which has an adverse effect on the S/R ratio, and on the other hand to an increase in the partial volume effect, so that the outlines of the structures are less clearly defined. The latter effect is clearly due to the increase in the width of the SSP. This increase becomes greater with coarser pitches, reducing the contrast resolution.

Trade-offs in resolution

Figure 4 shows the differences in resolution of a conventional scan with 5 mm collimation, spiral scans with the same collimation with pitches 1 and 1.4, and a 7 mm collimation with pitch 1. Comparing the axial scans, the conventional scan is superior to the other scans. In the spiral scans, artifacts cause contrast in homogeneous areas. This is more severe at the higher pitches. In theory the partial volume effects increase with increased slice thickness, but that is not very clear in these images. In the multiplanar reconstructions we see stairstep artifacts in the conventional acquisition. This artifact is largely reduced in the spiral acquisitions: the structures are more smoothly displayed, more conform the actual morphology. However, spiral artifacts do appear in these images: the amplitude increases with the pitch, the frequency reduces with the table increment per rotation. A thin slice with a small pitch gives the best spatial resolution.

A thin slice and small pitch give the best spatial resolution.

Examples

Because the choice of a thin slice is always associated with relatively low contrast resolution, long acquisition times, and short scannable volumes, choices have to be made in order to optimize the protocols for the envisaged application.

In multiphasic liver studies the complete liver has to be scanned within one minute.

High inherent contrast, requirement for high spatial resolution e.g. temporal bone
Maximum spatial resolution in the axial plane is achieved by scanning in the conventional way with a high-resolution filter. Some resolution can be lost, due to patient movement, making it preferable to select spiral acquisition. In view of the importance of the spatial resolution, the slice thickness and the table increment should be as small as possible (pitch 1).

High inherent contrast, limited requirements with respect to spatial resolution, need for speed e.g. CTA
For CT angiography (CTA) a bolus of contrast medium is injected intravenously. This will provide optimum contrast for a limited time. The complete acquisition must take place within this time. A slice thickness is selected of the same order of magnitude as that of the structures of interest, with a pitch of 1–1.5, to achieve complete imaging of the vessels. Where CTA is performed as preparation for a transplant, in which it is necessary to determine how many aberrant vessels there are, pitch 2 can be selected. If CTA is performed in order to determine the severity of a renal artery stenosis, pitch 1 must be selected.

High inherent contrast, low requirements with respect to spatial resolution e.g. pulmonary carcinoma
In this application, the precise shape of any abnormality that may be found is not important. A coarse pitch (up to 2) can be used, with the collimation related to the size of the lesions to be detected.

Low inherent contrast, limited requirements with respect to speed e.g. general abdominal examinations
A slice thickness is selected which will give just enough contrast resolution at the maximum permissible mA. Limiting the pitch to 1 reduces the artifacts arising from intestinal gas.

Low inherent contrast, need for speed e.g. multiphasic liver scan
In this application, the complete liver has to be scanned in the arterial phase within one minute, so that the portal phase can be scanned subsequently. To avoid significant loss of contrast resolution, the pitch chosen must not be too coarse (1–1.4).

Very low inherent contrast e.g. brain
In order to provide good visualization of the low contrast between grey and white matter, a high X-ray dose is required. This cannot be achieved with spiral acquisition. Conventional CT is therefore preferred. As mentioned earlier, spiral artifacts at the top of the brain may simulate subdural haematoma. For this reason, the top of the brain should never be scanned in spiral mode.

Effects on the X-ray dose

Spiral CT offers the possibility of multiphasic scans, in which data on a complete organ such as the liver can be acquired several times within a given time. Multiple scans are also made for other reasons, for example to perform CTA with the highest possible spatial resolution. The most important effects of spiral CT on dose are given below.

Dose, tube voltage and tube current
The voltage applied to the X-ray tube determines the energy of the X-ray spectrum. An aspect that is often overlooked is that the dose increases roughly with the square of the tube voltage. On the other hand, the dose increases in a linear relationship to the tube current and the scan time. Because these parameters are generally limited in spiral CT protocols, the dose is often lower than that in conventional CT. The total effect of voltage, current, geometry and filtration is expressed in the CT dose index (CTDI).

Dose and slice thickness
In contiguous scanning, that is conventional scanning with a table index equal to the slice thickness, or spiral scanning with pitch 1, the dose to the patient is, in principle, independent of the slice thickness. The amount of radiation emitted by the source is not affected by the subsequent collimation. The collimation prevents a certain proportion of the emitted photons from reaching the patient. The number of photons reaching the patient for a 2 mm slice is one third of the number of photons for a 6 mm slice (Fig. 5). Differences only occur due to the use of post-patient collimation, different focus sizes, and geometric effects. The differences seen in the CTDI values are principally the result of a non-optimal measuring method. For this reason, the European

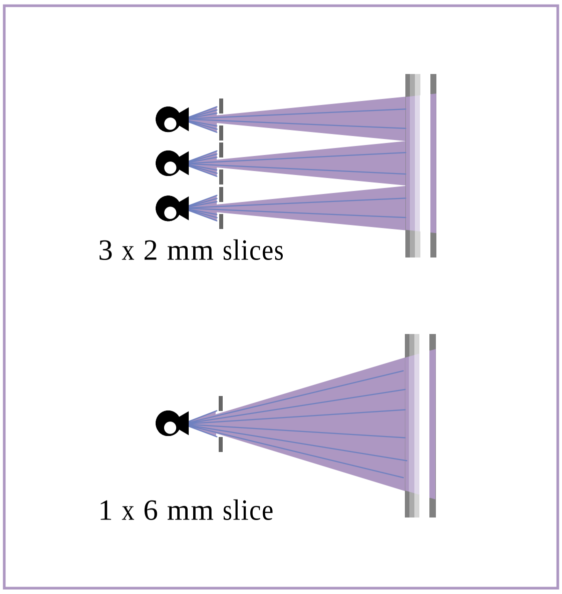

Fig. 5. In contiguous scanning, the dose is independent of the slice thickness: Due to collimation differences, the number of photons per slice reaching the patient scanned with a 2 mm slice is one third of the number of photons in a 6 mm slice. In contiguous scanning, three 2 mm slices are needed to cover the same volume as one 6 mm slice. The total amount of radiation for the patient is therefore the same.

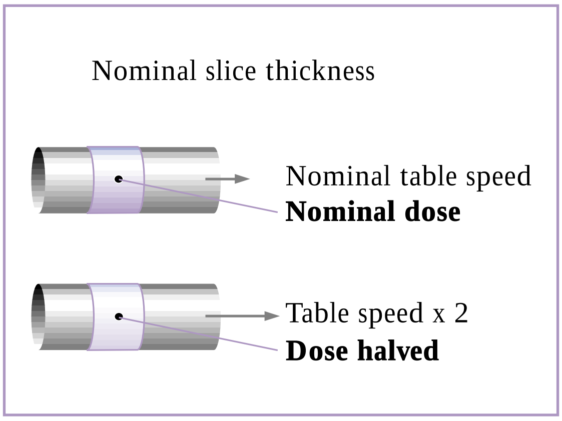

Fig. 6. If the dose increases by a factor 2, the centre of the patient is irradiated only half as long. Since the radiation per second emitted by the tube is independent of the table speed, the patient dose halves with doubled pitch.

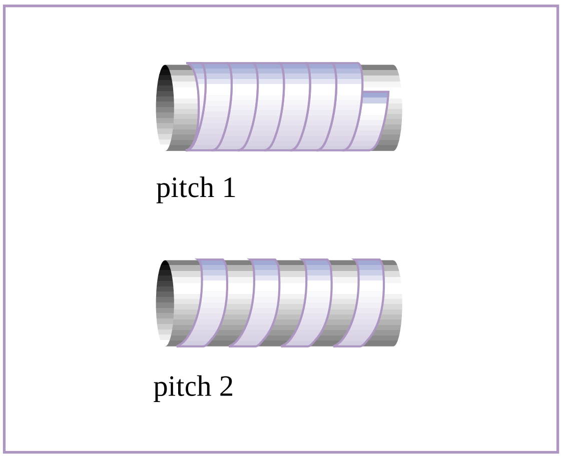

Fig. 7. Effects of the pitch on the skin dose: The most important factor is the direct radiation to the skin. With pitch 1, every part of the skin receives the same amount. With pitch 2, half of the skin receives the same amount of radiation as with pitch 1, the other half receives no direct radiation.

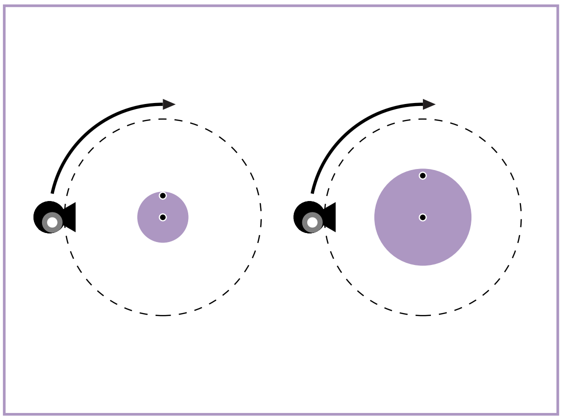

Fig. 8. In obese patients, the centre dose decreases due to the attenuation of the surrounding tissue. The net effect of the patient size on the skin dose depends on the beam filtration and scanner geometry.

Union will shortly introduce new guidelines for measuring the CTDI.

Dose and table increment/pitch
The dose values indicated by CTDI always refer to ‘contiguous’ scanning. In spiral CT, that is equivalent to scanning with pitch 1. The greater the selected pitch at any given nominal slice thickness, the faster the patient will move through the X-ray beam. The dose along the longitudinal axis of the patient is thus in inverse proportion to the pitch (Fig. 6).

Scanners cannot be compared simply by looking at the parameters.

The situation with the skin is somewhat different. If the selected pitch is greater than 1, some square centimetres of the patient’s skin will not receive the entrance dose, and will therefore be exposed to less radiation. Other areas will receive the same dose as with pitch 1 (Fig. 7). Because the risk associated with dose can be assumed to be in direct proportion to the dose, it can also be assumed that the risk due to stochastic radiation effects will be in inverse ratio to the pitch.

Some studies quote pitch 1.4 as the optimum compromise between spatial resolution, contrast resolution and dose [10]. However, these studies do not take spiral artifacts into account.

The received dose is strongly dependent on the patient’s size.

Dose and patient size
The dose that a patient receives is strongly dependent on the patient’s size. If the same protocols are used for all patients, the centre dose will be lower in obese patients due to the attenuation of the surrounding tissue. The following example may demonstrate how much the patient size influences the dose.
We can represent the abdomen of an adult patient by a water phantom with a diameter of 32 cm. If the water phantom is scanned in a given CT system at 100 mAs and 120 kV, with a slice thickness of 10 mm, the dose measured in the centre of the phantom will be 4.7 mGy, and that at the periphery will be 9.2 mGy. These values can be used as an estimate for the central dose and the skin dose in a patient with the same diameter, undergoing an abdominal scan. If a water phantom with a diameter of 16 cm is scanned with the same parameters on the same scanner, the values measured would then be 14.1 mGy in the centre, and 14.5 mGy at the periphery (Fig. 8). These values can then be used to estimate the dose for a child of the same diameter. In order to scan the child with the same centre dose as an adult, the mA value in the adult protocol must be reduced to 4.7/14.1 = 1/3. For images of similar quality with respect to image noise, the applied dose in the child can be reduced still further.

Dose, scanner geometry and filtration
Due to differences in the geometry and construction of various scanners, and the use of different shapes and materials for filtering the X-ray beam before it reaches the patient, the dose to the patient at the same mA and kV values can vary by as much as a factor 2. In general, in scanners with a short beam geometry, the mA value has to be reduced to obtain the same dose in the centre of the patient. The skin dose in these scanners is relatively high. Consequently scanners (and protocols) cannot be compared simply by looking at the parameters.

Viewing

In spiral CT, several reconstructions are generally made per rotation of the tube. This leads to a large number of images, all of which have to be assessed. In order to speed assessment of the scan, and to reduce the quantity of films, the reporting is often done with a combination of a viewing workstation and films. Sequences of images can be displayed on the workstation in a ‘movie’ or ‘cine’ mode. This has the great advantage that structures can easily be followed through the various images. An additional advantage is that the window width and level can be adapted interactively. Film continues to be of value, as it offers an overview. In order to save film costs, a selection of images can be made, such as every second reconstruction.

In Endoview techniques the viewpoint of the observer lies within the structure of interest.

A workstation can also be used for multiplanar reformatting (MPR). These images show planes through the patient in sagittal, coronal or oblique directions. They also help to provide a 3-dimensional impression of the patient. The workstations can, of course, also be used for advanced postprocessing techniques such as ‘maximum intensity projections’ (MIP), ‘surface rendering’ and ‘volume rendering’. ‘Endoview’ techniques are a special form of volume rendering in which the viewpoint of the observer lies within the structure of interest.

Conclusion

The development of the spiral technology has led to a rapid increase in the speed of acquisition. This has increased the 'patient throughput' for examinations of the trunk, and has made it possible to apply new diagnostic procedures. The elegance of CT is that, regardless of how the data are acquired, the only parameter that has to be considered is the attenuation value of the tissues. This makes CT, including spiral CT, a robust and easily understood procedure.

CT, including spiral CT, is a robust and easily understood procedure.

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