

Artifacts in CT: Recognition and Avoidance¹

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CME FEATURE

See accompanying test at http://www.rsna.org/education/rg_cme.html

LEARNING OBJECTIVES FOR TEST 5

After reading this article and taking the test, the reader will be able to:

- Identify the various types of artifacts that can appear in CT images.
- Discuss the reasons why these artifacts occur.
- Describe the methods of avoiding or suppressing artifacts available with modern CT systems.

Artifacts can seriously degrade the quality of computed tomographic (CT) images, sometimes to the point of making them diagnostically unusable. To optimize image quality, it is necessary to understand why artifacts occur and how they can be prevented or suppressed. CT artifacts originate from a range of sources. Physics-based artifacts result from the physical processes involved in the acquisition of CT data. Patient-based artifacts are caused by such factors as patient movement or the presence of metallic materials in or on the patient. Scanner-based artifacts result from imperfections in scanner function. Helical and multisection technique artifacts are produced by the image reconstruction process. Design features incorporated into modern CT scanners minimize some types of artifacts, and some can be partially corrected by the scanner software. However, in many instances, careful patient positioning and optimum selection of scanning parameters are the most important factors in avoiding CT artifacts.

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Index terms: Computed tomography (CT), artifact • Computed tomography (CT), image quality • Images, artifact • Images, quality

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Introduction

In computed tomography (CT), the term *artifact* is applied to any systematic discrepancy between the CT numbers in the reconstructed image and the true attenuation coefficients of the object. CT images are inherently more prone to artifacts than conventional radiographs because the image is reconstructed from something on the order of a million independent detector measurements. The reconstruction technique assumes that all these measurements are consistent, so any error of measurement will usually reflect itself as an error in the reconstructed image. The types of artifact that can occur are as follows: (a) streaking, which is generally due to an inconsistency in a single measurement; (b) shading, which is due to a group of channels or views deviating gradually from the true measurement; (c) rings, which are due to errors in an individual detector calibration; and (d) distortion, which is due to helical reconstruction.

It is possible to group the origins of these artifacts into four categories: (a) physics-based artifacts, which result from the physical processes involved in the acquisition of CT data; (b) patient-based artifacts, which are caused by such factors as patient movement or the presence of metallic materials in or on the patient; (c) scanner-based artifacts, which result from imperfections in scanner function; and (d) helical and multisection artifacts, which are produced by the image reconstruction process.

In this article, the different types of artifact within each of these categories will be described with regard to (a) the mechanisms by which they are generated, (b) the methods employed by CT equipment manufacturers to suppress them, and (c) techniques of artifact avoidance available to the operator.

Physics-based Artifacts

Beam Hardening

An x-ray beam is composed of individual photons with a range of energies. As the beam passes through an object, it becomes “harder,” that is to say its mean energy increases, because the lower-energy photons are absorbed more rapidly than the higher-energy photons (Fig 1). Two types of artifact can result from this effect: so-called cupping artifacts and the appearance of dark bands or streaks between dense objects in the image.

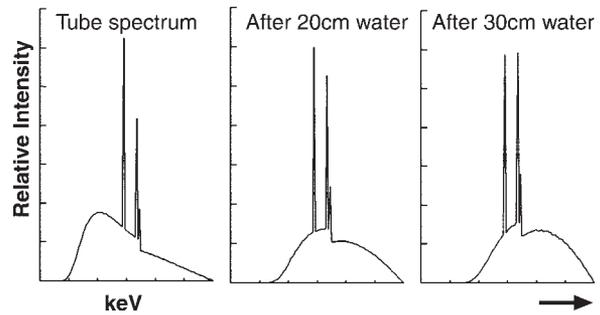


Figure 1. Changing energy spectrum of an x-ray beam as it passes through water. The mean energy increases with depth. (The attenuated spectra have been rescaled to be equivalent in size to the unattenuated spectra.)

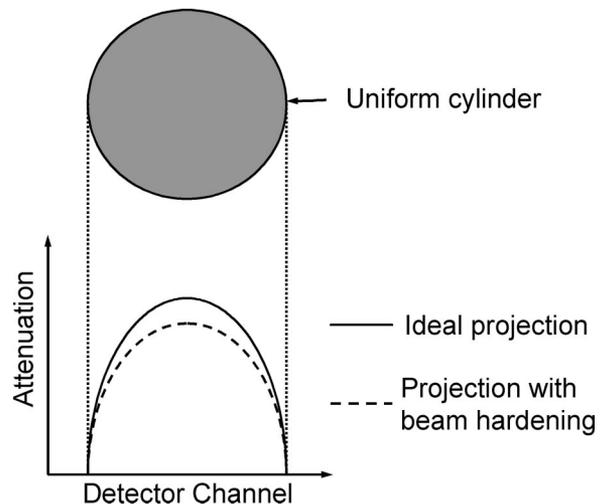
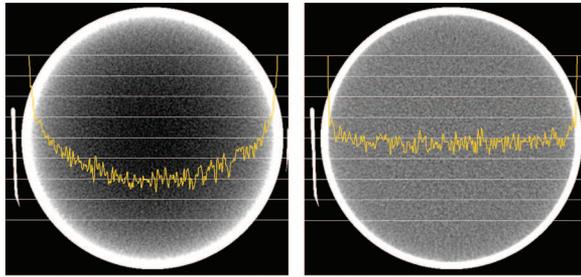


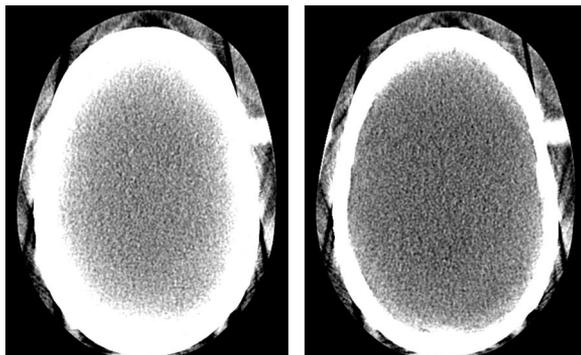
Figure 2. Attenuation profiles obtained with and without beam hardening for an x-ray beam passing through a uniform cylindrical phantom.

Cupping Artifacts.—X rays passing through the middle portion of a uniform cylindrical phantom are hardened more than those passing through the edges because they are passing through more material. As the beam becomes harder, the rate at which it is attenuated decreases, so the beam is more intense when it reaches the detectors than would be expected if it had not been hardened. Therefore, the resultant attenuation profile differs from the ideal profile that would be obtained without beam hardening (Fig 2). A profile of the CT numbers across the phantom displays a characteristic cupped shape (Fig 3a).

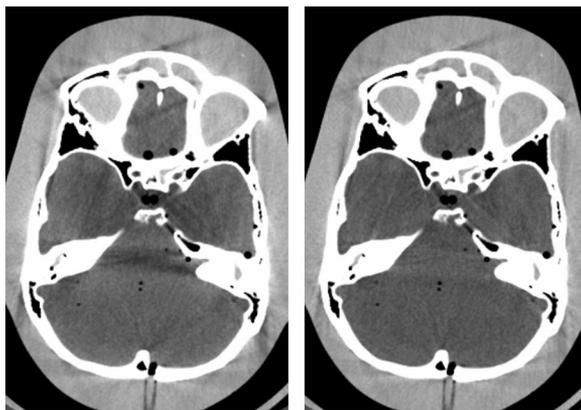
Streaks and Dark Bands.—In very heterogeneous cross sections, dark bands or streaks can appear between two dense objects in an image. They occur because the portion of the beam that passes through one of the objects at certain tube



a. **b.**
Figure 3. CT number profiles obtained across the center of a uniform water phantom without calibration correction (a) and with calibration correction (b).



a. **b.**
Figure 5. CT images of a skull phantom reconstructed without bone correction (a) and with bone correction (b).



a. **b.**
Figure 6. CT images of the posterior fossa show the dark banding that occurs between dense objects when only calibration correction is applied (a) and the reduction in artifacts when iterative beam hardening correction is also applied (b). (Reprinted, with permission, from reference 1.)

positions is hardened less than when it passes through both objects at other tube positions. This type of artifact can occur both in bony regions of the body and in scans where a contrast medium



Figure 4. CT image shows streaking artifacts due to the beam hardening effects of contrast medium.

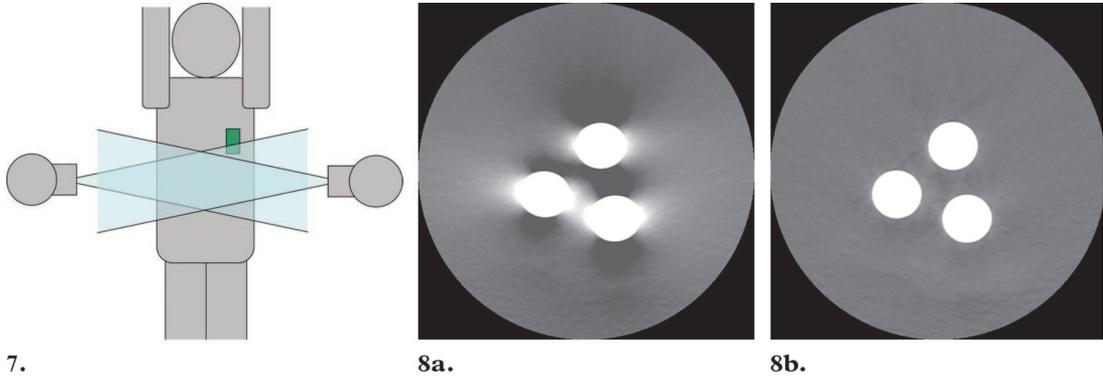
has been used. In the chest scan shown in Figure 4, the contrast medium has caused artifacts that might be mistaken for disease in nearby anatomy.

Built-in Features for Minimizing Beam Hardening.—Manufacturers minimize beam hardening by using filtration, calibration correction, and beam hardening correction software.

Filtration: A flat piece of attenuating, usually metallic material is used to “pre-harden” the beam by filtering out the lower-energy components before it passes through the patient. An additional “bowtie” filter further hardens the edges of the beam, which will pass through the thinner parts of the patient.

Calibration correction: Manufacturers calibrate their scanners using phantoms in a range of sizes. This allows the detectors to be calibrated with compensation tailored for the beam hardening effects of different parts of the patient. Figure 3b demonstrates the elimination of cupping artifacts by this means in a phantom. Since patient anatomy never exactly matches a cylindrical calibration phantom, in clinical practice there may be either a slight residual cupping artifact or a slight “capping” artifact, with a higher central CT value due to overcorrection.

Beam hardening correction software: An iterative correction algorithm may be applied when images of bony regions are being reconstructed. This helps minimize blurring of the bone–soft tissue interface in brain scans (Fig 5) and also reduces the appearance of dark bands in nonhomogeneous cross sections (Fig 6).



7.

8a.

8b.

Figures 7, 8. (7) Mechanism of partial volume artifacts, which occur when a dense object lying off-center protrudes part of the way into the x-ray beam. (8) CT images of three 12-mm-diameter acrylic rods supported in air parallel to and approximately 15 cm from the scanner axis. (a) Image obtained with the rods partially intruded into the section width shows partial volume artifacts. (b) Image obtained with the rods fully intruded into the section width shows no partial volume artifacts.

Avoidance of Beam Hardening by the Operator.—It is sometimes possible to avoid scanning bony regions, either by means of patient positioning or by tilting the gantry. It is important to select the appropriate scan field of view to ensure that the scanner uses the correct calibration and beam hardening correction data and, on some systems, the appropriate bowtie filter.

Partial Volume

There are a number of ways in which the partial volume effect can lead to image artifacts. These artifacts are a separate problem from partial volume averaging, which yields a CT number representative of the average attenuation of the materials within a voxel.

One type of partial volume artifact occurs when a dense object lying off-center protrudes partway into the width of the x-ray beam. In Figure 7, the divergence of the x-ray beam along the z axis has been greatly exaggerated to demonstrate how such an off-axis object can be within the beam, and therefore “seen” by the detectors, when the tube is pointing from left to right but outside the beam, and therefore not seen by the detectors, when the tube is pointing from right to left. The inconsistencies between the views cause shading artifacts to appear in the image (Fig 8a).

Partial volume artifacts can best be avoided by using a thin acquisition section width. This is necessary when imaging any part of the body where the anatomy is changing rapidly in the z



Figure 9. CT image of a shoulder phantom shows streaking artifacts caused by photon starvation.

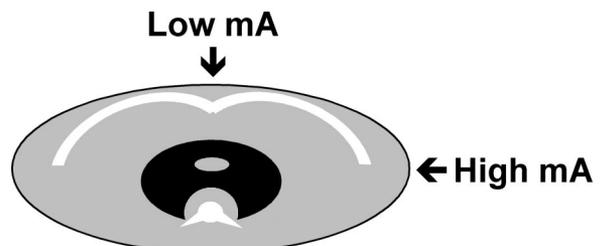


Figure 10. Tube current modulation as a function of tube angle. *mA* = milliamperage.

direction, for example in the posterior fossa. To limit image noise, thicker sections can be generated by adding together several thin sections.

Photon Starvation

A potential source of serious streaking artifacts is photon starvation, which can occur in highly attenuating areas such as the shoulders (Fig 9). When the x-ray beam is traveling horizontally, the attenuation is greatest and insufficient photons

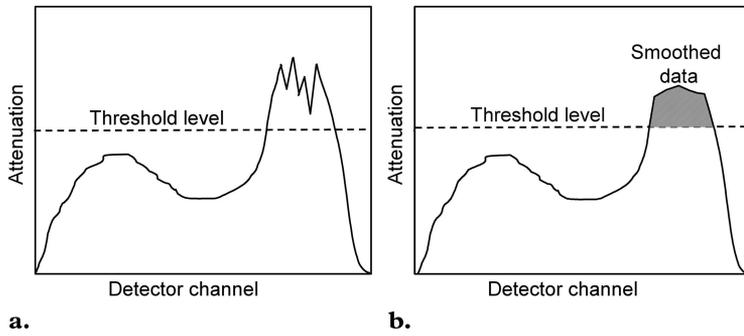


Figure 11. Projection data as they might appear for a horizontal x-ray beam passing through the shoulders. Diagrams show the data in their original form (a) and with adaptive filtration (b).

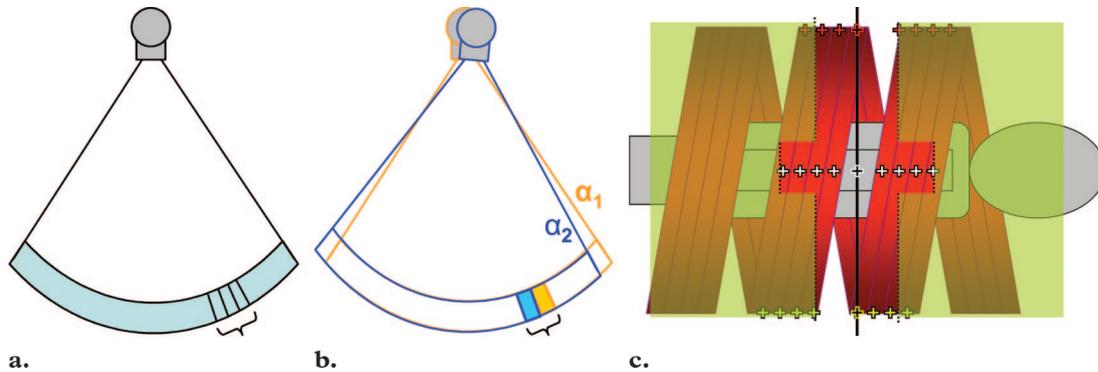


Figure 12. The three components of multidimensional adaptive filtration: averaging of adjacent in-plane detector readings (a), averaging of each detector reading at successive projection angles (b), and broadening of the z filter for high-attenuation angles (c). Black line in c = reconstruction position.

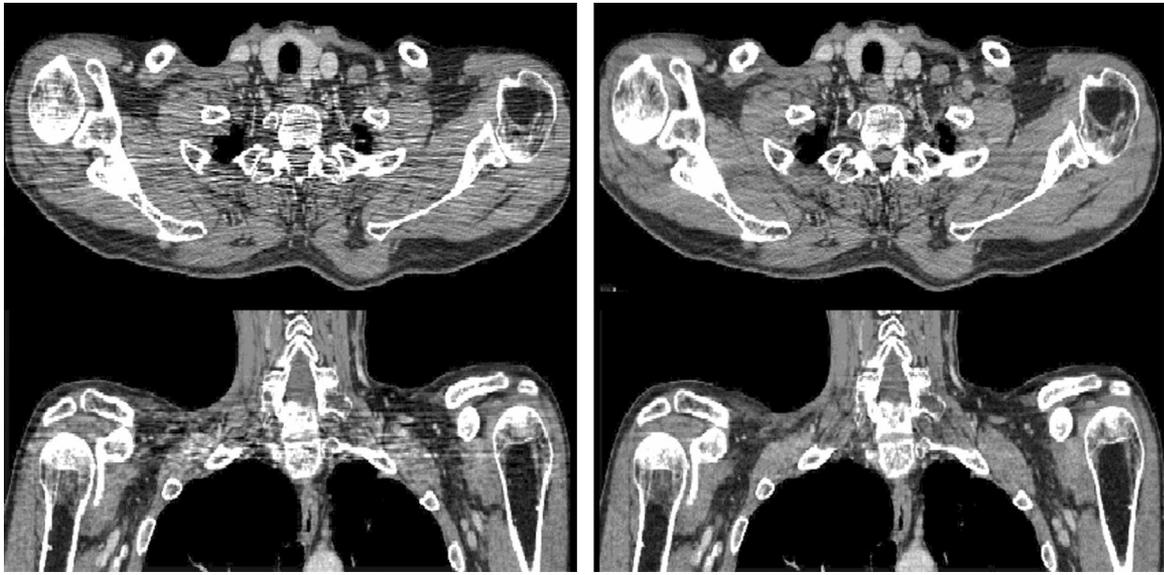
reach the detectors. The result is that very noisy projections are produced at these tube angulations. The reconstruction process has the effect of greatly magnifying the noise, resulting in horizontal streaks in the image.

If the tube current is increased for the duration of the scan, the problem of photon starvation will be overcome, but the patient will receive an unnecessary dose when the beam is passing through less attenuating parts. Therefore, manufacturers have developed techniques for minimizing photon starvation.

Automatic Tube Current Modulation.—On some scanner models, the tube current is automatically varied during the course of each rotation, a process known as *milliamperage modulation*. This allows sufficient photons to pass through the widest parts of the patient without unnecessary dose to the narrower parts (Fig 10).

Adaptive Filtration.—Some manufacturers use a type of adaptive filtration to reduce the streaking in photon-starved images. This software correction smooths the attenuation profile in areas of high attenuation before the image is reconstructed (Fig 11).

A multidimensional adaptive filtration technique is currently being developed for use on multisection scanners. For the small proportion of projection data that exceed a selected attenuation threshold, smoothing is carried out between adjacent in-plane detectors (Fig 12a) and between successive projection angles (Fig 12b), while the z filter used in helical reconstruction is broadened for high-attenuation projection angles to allow more photons to contribute to



a. **Figure 13.** Original axial CT images (top) and coronal reformatted images (bottom) in their original form (**a**) and after reconstruction with multidimensional adaptive filtration (**b**). (Courtesy of Willi Kalender, PhD, University of Erlangen, Germany.)

the reconstruction (Fig 12c). Figure 13 demonstrates the degree to which streaking is reduced while maintaining spatial resolution with the technique (2).

Undersampling

The number of projections used to reconstruct a CT image is one of the determining factors in image quality. Too large an interval between projections (undersampling) can result in misregistration by the computer of information relating to sharp edges and small objects. This leads to an effect known as *view aliasing*, where fine stripes appear to be radiating from the edge of, but at a distance from, a dense structure (Fig 14). Stripes appearing close to the structure are more likely to be caused by undersampling within a projection, which is known as *ray aliasing*.

Aliasing may not have too serious an effect on the diagnostic quality of an image, since the evenly spaced lines do not normally mimic any anatomic structures. However, where resolution of fine detail is important, undersampling artifacts

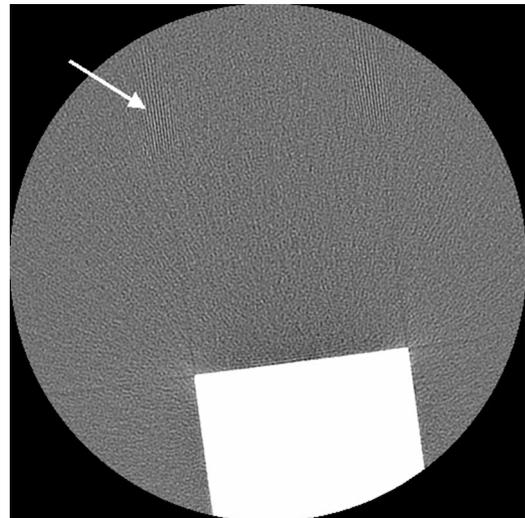


Figure 14. CT image of a Teflon block in a water phantom shows aliasing (arrow) due to undersampling of the edge of the block.

need to be avoided as far as possible. View aliasing can be minimized by acquiring the largest possible number of projections per rotation. On some scanners, this can be achieved only by using a slower rotation speed, while on others the number of projections is independent of rotation speed. Ray aliasing can be reduced by using specialized high-resolution techniques, such as quarter-detector shift or flying focal spot, which manufacturers employ to increase the number of samples within a projection.



a. **b.**
Figure 15. CT images of a patient with metal spine implants, reconstructed without any correction (**a**) and with metal artifact reduction (**b**). (Courtesy of Siemens, Forchheim, Germany.)



Figure 16. CT image of the head shows motion artifacts.

Patient-based Artifacts

Metallic Materials

The presence of metal objects in the scan field can lead to severe streaking artifacts. They occur because the density of the metal is beyond the normal range that can be handled by the computer, resulting in incomplete attenuation profiles. Additional artifacts due to beam hardening, partial volume, and aliasing are likely to compound the problem when scanning very dense objects.

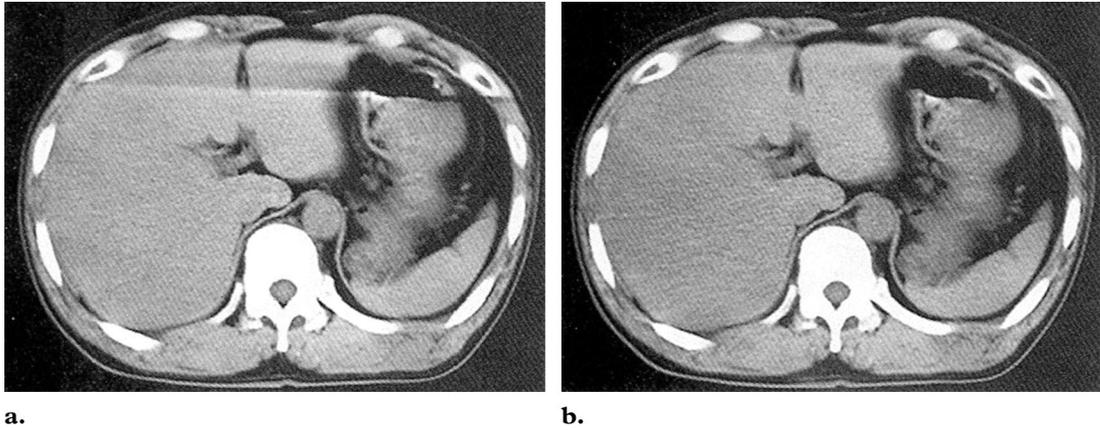
Avoidance of Metal Artifacts by the Operator.—Patients are normally asked to take off removable metal objects such as jewelry before

scanning commences. For nonremovable items, such as dental fillings, prosthetic devices, and surgical clips, it is sometimes possible to use gantry angulation to exclude the metal inserts from scans of nearby anatomy. When it is impossible to scan the required anatomy without including metal objects, increasing technique, especially kilovoltage, may help penetrate some objects, and using thin sections will reduce the contribution due to partial volume artifact.

Software Corrections for Metal Artifacts.—Streaking caused by overranging can be greatly reduced by means of special software corrections. Manufacturers use a variety of interpolation techniques to substitute the overrange values in attenuation profiles. The effectiveness of one such technique is illustrated in Figure 15. The usefulness of metal artifact reduction software is sometimes limited because, although streaking distant from the metal implants is removed, there still remains a loss of detail around the metal-tissue interface, which is often the main area of diagnostic interest. Beam hardening correction software should also be used when scanning metal objects to minimize the additional artifacts due to beam hardening.

Patient Motion

Patient motion can cause misregistration artifacts, which usually appear as shading or streaking in the reconstructed image (Fig 16). Steps can be taken to prevent voluntary motion, but some involuntary motion may be unavoidable during



a. **b.**
Figure 17. CT images of the body created with conventional reconstruction (**a**) and with motion artifact correction (**b**). (Reprinted, with permission, from reference 3.)

body scanning. However, there are special features on some scanners designed to minimize the resulting artifacts.

Avoidance of Motion Artifacts by the Operator.—The use of positioning aids is sufficient to prevent voluntary movement in most patients. However, in some cases (eg, pediatric patients), it may be necessary to immobilize the patient by means of sedation. Using as short a scan time as possible helps minimize artifacts when scanning regions prone to movement. Respiratory motion can be minimized if patients are able to hold their breath for the duration of the scan.

The sensitivity of the image to motion artifacts depends on the orientation of the motion. Therefore, it is preferable if the start and end position of the tube is aligned with the primary direction of motion, for example, vertically above or below a patient undergoing a chest scan. Specifying body scan mode, as opposed to head scan mode, may automatically incorporate some motion artifact reduction in the reconstruction.

Built-in Features for Minimizing Motion Artifacts.—Manufacturers minimize motion artifacts by using overscan and underscan modes, software correction, and cardiac gating.

Overscan and underscan modes: The maximum discrepancy in detector readings occurs between views obtained toward the beginning and end of a 360° scan. Some scanner models use overscan mode for axial body scans, whereby an extra 10% or so is added to the standard 360° rotation. The repeated projections are averaged,

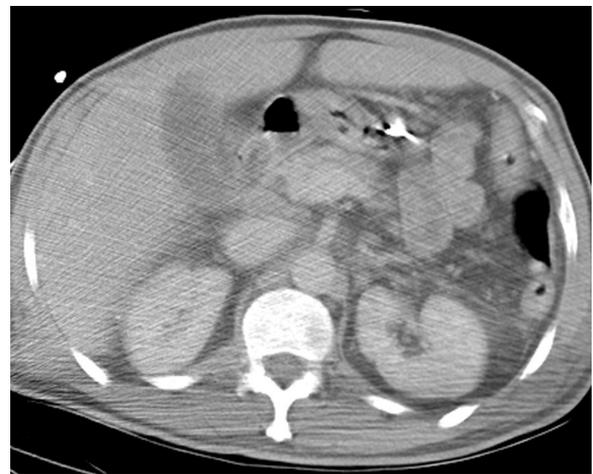


Figure 18. CT image of the body obtained with the patient's arms down but outside the scanning field shows streaking artifacts.

which helps reduce the severity of motion artifacts. The use of partial scan mode can also reduce motion artifacts, but this may be at the expense of poorer resolution.

Software correction: Most scanners, when used in body scan mode, automatically apply reduced weighting to the beginning and end views to suppress their contribution to the final image. However, this may lead to more noise in the vertical direction of the resultant image, depending on the shape of the patient. Additional, specialized motion correction is available on some scanners. The effectiveness of one such technique in correcting artifacts due to motion of a fluid interface is demonstrated in Figure 17.

Cardiac gating: The rapid motion of the heart can lead to severe artifacts in images of the heart and to artifacts that can mimic disease in associ-

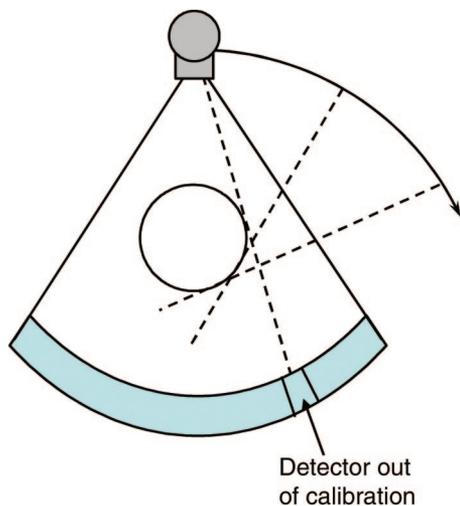


Figure 19. Formation of a ring artifact when a detector is out of calibration.

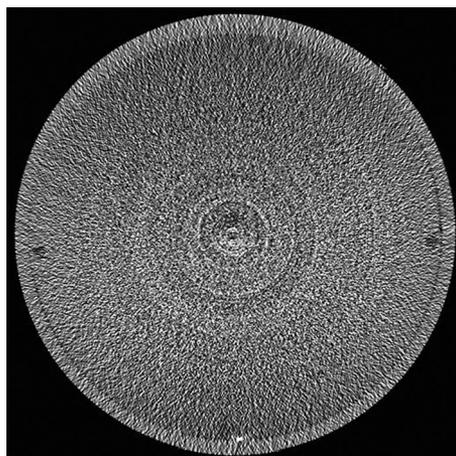


Figure 20. CT image of a water-filled phantom shows ring artifacts.

ated structures, for example, dissected aorta. To overcome these difficulties, techniques have been developed to produce images by using data from just a fraction of the cardiac cycle, when there is least cardiac motion. This is achieved by combining electrocardiographic gating techniques with specialized methods of image reconstruction (4).

Incomplete Projections

If any portion of the patient lies outside the scan field of view, the computer will have incomplete information relating to this portion and streaking or shading artifacts are likely to be generated. This is illustrated in Figure 18, which shows a patient scanned with the arms down instead of being raised out of the way of the scan. As the

arms are outside the scan field, they are not present in the image, but their presence in some views during scanning has led to such severe artifacts throughout the image as to significantly degrade its usefulness. Similar effects can be caused by dense objects such as an intravenous tube containing contrast medium lying outside the scan field. Blocking of the reference channels at the sides of the detector array may also interfere with data normalization and cause streaking artifacts.

To avoid artifacts due to incomplete projections, it is essential to position the patient so that no parts lie outside the scan field. Scanners designed specifically for radiation therapy planning have wider bores and larger scan fields of view than standard scanners and permit greater versatility in patient positioning. They also allow scanning of exceptionally large patients who would not fit within the field of view of standard scanners.

Some manufacturers monitor the reference data channels for inconsistencies and avoid using reference data that appear suspicious. As an alternative, the CT system may be designed with reference detectors on the tube side or with ray paths within the gantry to eliminate possible interference with reference data.

Scanner-based Artifacts

Ring Artifacts

If one of the detectors is out of calibration on a third-generation (rotating x-ray tube and detector assembly) scanner, the detector will give a consistently erroneous reading at each angular position, resulting in a circular artifact (Fig 19). A scanner with solid-state detectors, where all the detectors are separate entities, is in principle more susceptible to ring artifacts than a scanner with gas detectors, in which the detector array consists of a single xenon-filled chamber subdivided by electrodes.

Rings visible in a uniform phantom (Fig 20) or in air might not be visible on a clinical image if a wide window is used. Even if they are visible, they would rarely be confused with disease. However, they can impair the diagnostic quality of an image, and this is particularly likely when central detectors are affected, creating a dark smudge at the center of the image.

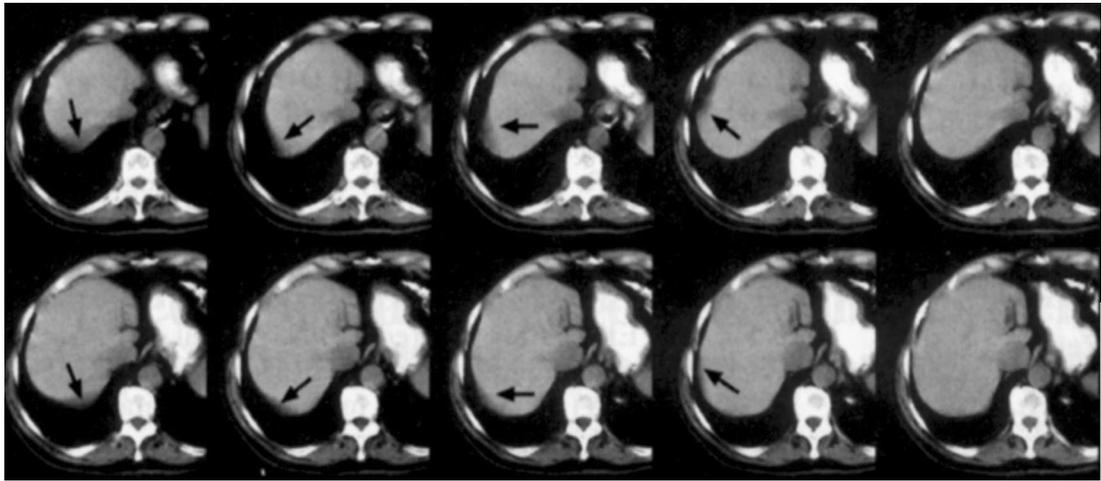


Figure 22. Series of CT images from a helical scan of the abdomen shows helical artifacts (arrows). (Reprinted, with permission, from reference 5.)

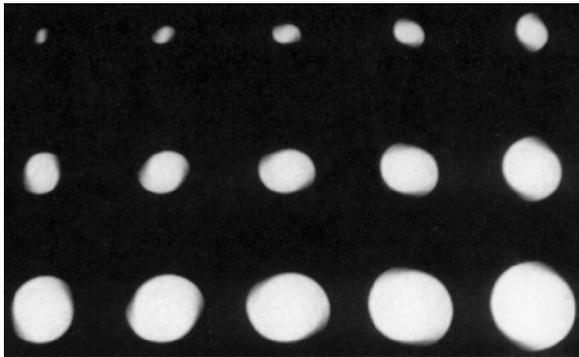


Figure 21. Consecutive axial CT images from a helical scan of a cone-shaped phantom lying along the scanner axis. (Reprinted, with permission, from reference 5.)

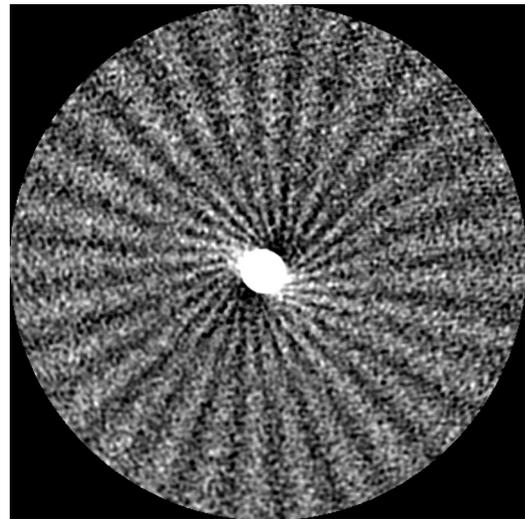


Figure 23. CT image of a 12-mm-diameter acrylic sphere supported in air, obtained with 0.6-mm section acquisition and beam pitch of 1.75, shows windmill artifact.

Avoidance and Software Corrections

The presence of circular artifacts in an image is an indication that the detector gain needs recalibration or may need repair services. Selecting the correct scan field of view may reduce the artifact by using calibration data that fit more closely to the patient anatomy.

All modern scanners use solid-state detectors, but their potential for ring artifacts is reduced by software that characterizes and corrects detector variations.

Helical and Multisection CT Artifacts

Helical Artifacts in the Axial Plane: Single-Section Scanning

In general, the same artifacts are seen in helical scanning as in sequential scanning. However,

there are additional artifacts that can occur in helical scanning due to the helical interpolation and reconstruction process. The artifacts occur when anatomic structures change rapidly in the z direction (eg, at the top of the skull) and are worse for higher pitches.

If a helical scan is performed of a cone-shaped phantom lying along the z axis of the scanner, the resultant axial images should appear circular. In fact, their shape is distorted because of the weighting function used in the helical interpolation algorithm (Fig 21). For some projection angles, the image is influenced more by contributions from wider parts of the cone in front of the scan plane; for other projection angles, contributions from narrower parts of the cone behind the

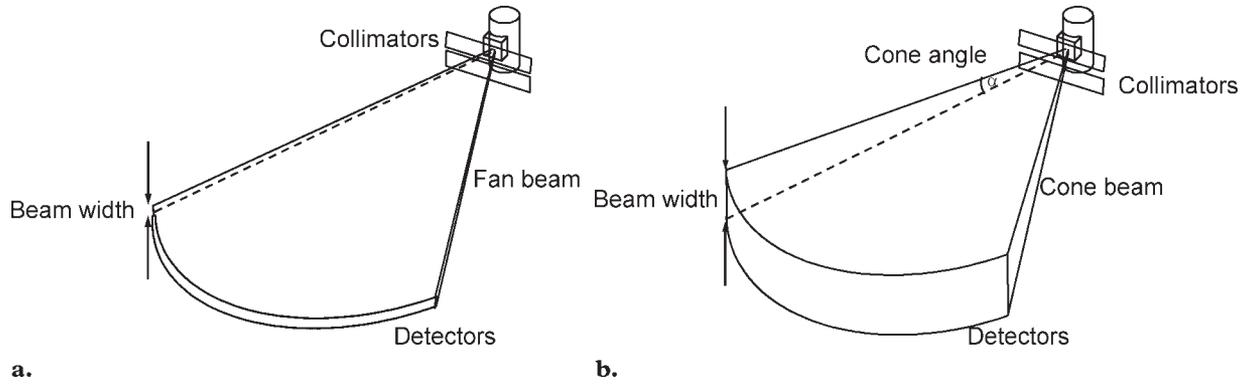


Figure 24. (a) Fan beam acquisition as used in single-section scanners. (b) Cone beam acquisition as used in multisection scanners.

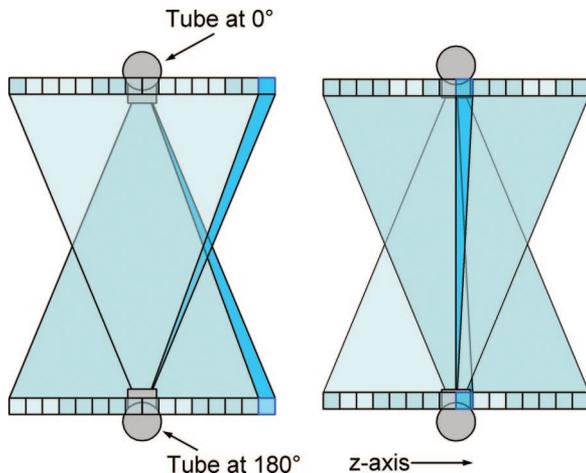


Figure 25. Volume of data collected by an outer row of detectors (left) and an inner row (right) on a 16-section scanner.

scan plane predominate. Thus, the orientation of the artifact changes as a function of the tube position at the center of the image plane. In clinical images, such as the series of liver images shown in Figure 22, helical artifacts can easily be misinterpreted as disease.

To keep helical artifacts to a minimum, steps must be taken to reduce the effects of variation along the z axis. This means using, where possible, a low pitch, a 180° rather than 360° helical interpolator if there is a choice, and thin acquisition sections rather than thick. Sometimes, it is still preferable to use axial rather than helical imaging to avoid helical artifacts (eg, in brain scanning).

Helical Artifacts in Multisection Scanning

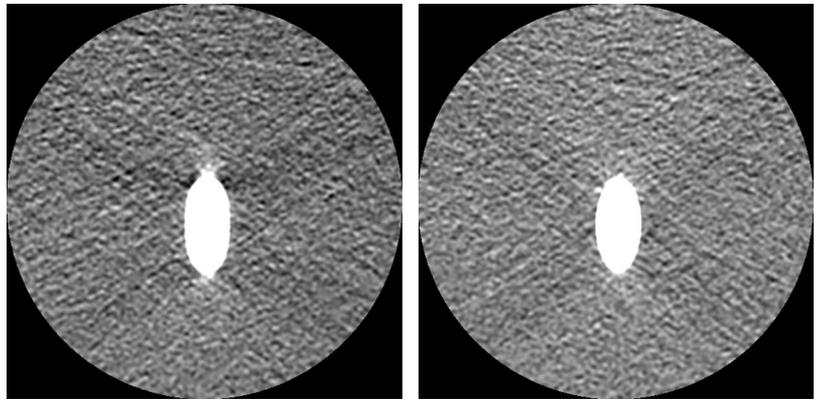
The helical interpolation process leads to a more complicated form of axial image distortion on multisection scanners than is seen on single-section

scanners. The typical windmill-like appearance of such artifacts (Fig 23) is due to the fact that several rows of detectors intersect the plane of reconstruction during the course of each rotation. As helical pitch increases, the number of detector rows intersecting the image plane per rotation increases and the number of “vanes” in the windmill artifact increases.

Z-filter helical interpolators are commonly used on multisection scanners to replace the two-point interpolators usually used on single-section scanners. One of the benefits of z-filter interpolators is that they reduce the severity of windmill artifacts, especially when the image reconstruction width is wider than the detector acquisition width. Artifacts may also be slightly reduced by using noninteger pitch values relative to detector acquisition width, such as pitches of 3.5 or 4.5 on a four-section scanner (6). This is because z-axis sampling density is optimized for noninteger pitches.

Cone Beam Effect

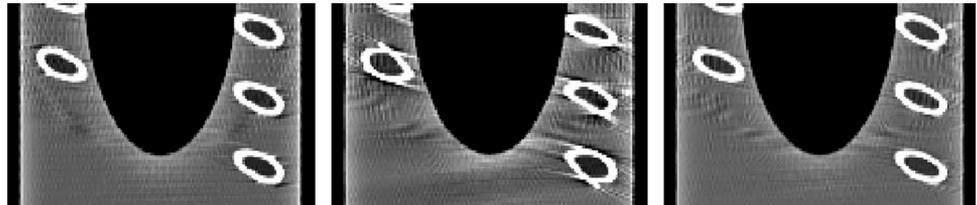
As the number of sections acquired per rotation increases, a wider collimation is required and the x-ray beam becomes cone-shaped rather than fan-shaped (Fig 24). Figure 25 shows an exaggerated view of the x-ray beam and detectors along the z axis. As the tube and detectors rotate around the patient (in a plane perpendicular to the diagram), the data collected by each detector correspond to a volume contained between two cones, instead of the ideal flat plane. This leads to artifacts similar to those caused by partial volume around off-axis objects. The artifacts are more pronounced for the outer detector rows than for the inner ones (Fig 26), where the data collected correspond more closely to a plane.



a.

b.

Figure 26. CT images from data collected by an outer detector row (a) and an inner detector row (b) show cone beam artifacts around a Teflon rod, which was positioned 70 mm from the isocenter at an angle of 60° to the scanner axis.

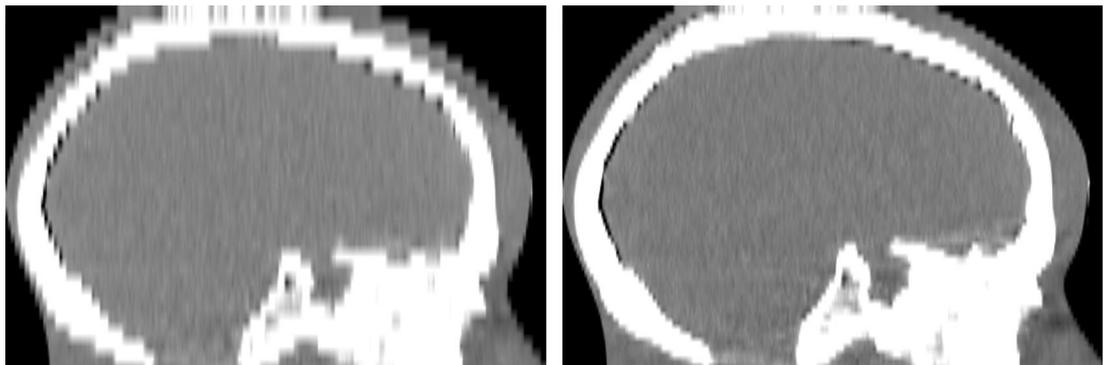


a.

b.

c.

Figure 27. CT images of a phantom, obtained by using four-section acquisition and standard reconstruction (a), 16-section acquisition and standard reconstruction (b), and 16-section acquisition and cone beam reconstruction (c). (Courtesy of Siemens.)



a.

b.

Figure 28. (a) Sagittal reformatted image from axial CT data obtained with 5-mm collimation and a 5-mm reconstruction interval. (b) Sagittal reformatted image from single-section helical CT data obtained with 5-mm collimation and a 2.5-mm reconstruction interval.

Cone beam effects get worse for increasing numbers of detector rows. Thus, 16-section scanners should potentially be more badly affected by artifacts than four-section scanners. However, manufacturers have addressed the problem by employing various forms of cone beam reconstruction instead of the standard reconstruction techniques used on four-section scanners. The effectiveness of one such technique is demonstrated in the phantom study shown in Figure 27.

Multiplanar and Three-dimensional Reformation

Major improvements in multiplanar and three-dimensional reformation have come about since the introduction of helical scanning and, to an even greater extent, with multisection scanning. The faster speed with which the required volume can be scanned means that the effects of patient motion are much reduced, and the use of narrower acquisition sections and overlapping reconstructed sections leads to sharper edge definition on reformatted images.

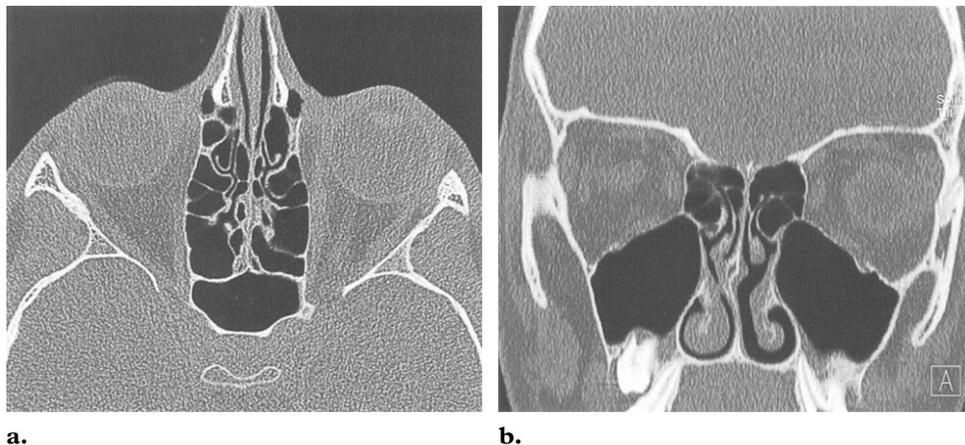


Figure 29. Original axial CT image (a) and coronal reformatted image (b) of the sinuses, obtained with a 16-section scanner by using thin acquisition sections. (Courtesy of Siemens [7].)

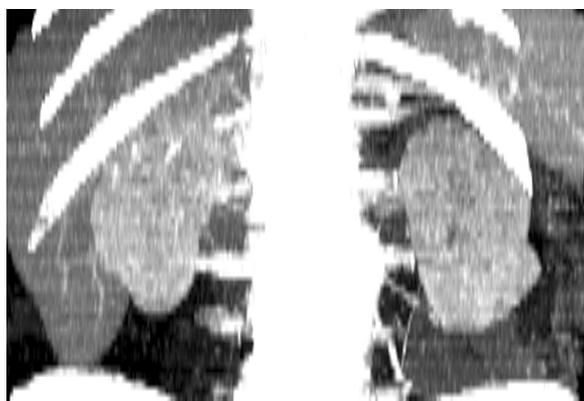


Figure 30. Maximum intensity projection image obtained with helical CT shows zebra artifacts.

Stair Step Artifacts.—Stair step artifacts appear around the edges of structures in multiplanar and three-dimensional reformatted images when wide collimations and nonoverlapping reconstruction intervals are used. They are less severe with helical scanning, which permits reconstruction of overlapping sections without the extra dose to the patient that would occur if overlapping axial scans were obtained (Fig 28). Stair step artifacts are virtually eliminated in multiplanar and three-dimensional reformatted images from thin-section data obtained with today's multisection scanners (Fig 29).

Zebra Artifacts.—Faint stripes may be apparent in multiplanar and three-dimensional reformatted images from helical data because the helical interpolation process gives rise to a degree of noise inhomogeneity along the z axis. This “zebra” effect (Fig 30) becomes more pronounced away

from the axis of rotation because the noise inhomogeneity is worse off-axis.

Summary

Artifacts originate from a range of sources and can degrade the quality of a CT image to varying degrees. Design features incorporated into modern scanners minimize some types of artifact, and some can be partially corrected by the scanner software. However, there are many instances where careful patient positioning and the optimum selection of scan parameters are the most important factors in avoiding image artifacts.

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