Helical CT: Principles and Technical Considerations

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INTRODUCTION
Helical computed tomography (CT) offers several technical advantages that have revolutionized body CT. Use of helical technology has improved established CT applications by the minimization of motion artifacts, the elimination of respiratory misregistration artifacts (1,2), and the production of overlapping images without additional x-ray exposure (3-5). New applications involving multidimensional imaging have been made possible by these advancements, of which CT angiography is but one example (6-8). High-quality three-dimensional images can be generated from multiple overlapping transaxial images acquired in a single breath hold.

Helical CT involves simultaneous translatory movement of the patient through the gantry while the x-ray source rotates such that continuous data acquisition is achieved throughout the volume of interest (1,2). The x-ray traces a helix on the patient’s surface, resulting in a helix of raw projection data from which planar images must be generated (Fig 1). Each rotation of the x-ray tube can be thought of as generating data specific to an angled plane of section (9). To achieve a true transaxial image, data points above and below the desired plane of section must be interpolated to estimate the data value in the transaxial plane (Fig 2). As a benefit, the interval between reconstructed transaxial images can be chosen arbitrarily and retrospectively.

INTERPOLATION ALGORITHMS
The early versions of helical CT employed a 360° linear interpolation algorithm such that data at a desired plane of section were generated by interpolating points separated by a full 360° rotation of the x-ray tube. This resulted in transaxial images that were nearly identical to those produced with conventional CT. However, longitudinally reformatted images showed rather prominent blurring, compared with the images reformatted from conventional scans (10). This prompted investigators to improve longitudinal resolution with algorithms that used data closer to the desired plane of section, with interpolated points separated by about a one-half rotation (180°) of the x-ray tube (2,11). One such algorithm performed simple linear interpolation, and another performed higher-order (cubic-spline) interpolation. Longitudinal resolution was improved with these 180° interpolation algorithms (Fig 3).

Index terms: Computed tomography (CT), helical technology • Computed tomography (CT), physics


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Figure 1. Diagram shows the scanning geometry in helical CT. $t_s = \text{time in seconds}$, $z = \text{section position}$. (Reprinted, with permission, from reference 1.)

Figure 2. Diagram illustrates the interpolation rationale for helical CT. Data from each rotation of the x-ray tube are specific to an angled plane of section. Data for transaxial sections must be generated by interpolation of data above and below the desired plane of section. $t = \text{index to position in the detector array}$, $z = \text{longitudinal position of patient cross section}$, $\theta = \text{rotation angle with a period of 360°}$. (Reprinted, with permission, from reference 9.)

The clinical advantages of these improvements in interpolation are twofold. First, high-resolution multiplanar and three-dimensional imaging are possible without significant longitudinal blurring. Second, and as an added benefit, the newer algorithms permit scanning at a pitch greater than 1, which affords greater coverage with any given helical technique (pitch is equal to the table increment per 360° rotation of the x-ray tube divided by the collimation). Practically, pitch is not increased above 2 because the broadening of section profiles becomes prohibitive at higher pitch values. Simulated results by Polacin et al (11) show the relationship between section thickness and pitch for 360° linear interpolation relative to 180° linear and cubic-spline interpolation algorithms (Fig 4). With a pitch of 2 and 360° interpolation, section thickness (defined in this case as the full width at tenth maximum of the section sensitivity profile) is increased threefold compared with that used in conventional CT. In contrast, the same parameter is increased by only 50% above that of conventional scanning when 180° interpolation is employed.

The newer interpolation algorithms have their disadvantages. The most important of these is an increase in image noise by 12%–29% for the 180° algorithms compared with that of conventional CT (2,11,12). Interestingly, noise with 360° linear interpolation is decreased by 17% compared with that in conventional scanning because of the relative increase in photon statistics associated with such a broad interpolation range. A second disadvantage, which we have observed only with the 180° higher-order (cubic-spline) interpolation method, is an artifact at high-contrast transverse interfaces on longitudinal reformatted images. This “breakup” artifact is shown on the coronal reformatted image of a fracture displacement phantom.
Figure 3. Section-sensitivity profiles for different helical CT interpolation algorithms (5-mm collimation, pitch of 1). The profiles for the 180° interpolation algorithms (180 LI, 180 HI) nearly approximate that of the rectangularly shaped profile for conventional CT (solid line). 180 HI = 180° higher-order (cubic-spline) interpolation, 180 LI = 180° linear interpolation, 360 LI = 360° linear interpolation, d = table feed (mm/sec). Rel = relative, Zpos = longitudinal position. (Reprinted, with permission, from reference 11.)

Figure 4. Graph compares section thickness versus pitch for three different interpolation algorithms. A substantial improvement in section thickness broadening is seen with 180° interpolation algorithms (180 LI, 180 HI) for a pitch greater than 1, as compared with that for 360° linear interpolation (360 LI). The graph displays simulated section thickness (defined here as the full width at tenth maximum of the section-sensitivity profile) for helical CT performed with 5-mm collimation. Pitch of 0 refers to conventional scanning. 180 HI = 180° higher-order (cubic-spline) interpolation, 180 LI = 180° linear interpolation. (Reprinted, with permission, from reference 11.)

Figure 5. Multiplanar reformatted image (right) of a fracture displacement phantom acquired with the helical technique (2-mm collimation, pitch of 1, 180° cubic-spline interpolation) reveals discontinuity of the phantom surface (horizontal arrow) orthogonal to the direction of table travel (vertical arrow). The breakup artifact was seen when 180° higher-order (cubic-spline) interpolation was used but not with 360° linear or 180° linear interpolation.

in Figure 5 (13). The smooth presenting surface of the phantom (orthogonal to the direction of table travel) is poorly rendered, with "breaking up" of the edge. This artifact has not been seen with 360° or 180° linear interpolation and may be caused by edge ringing or other interpolation artifact. Because of this artifact, we have excluded 180° cubic-spline interpolation from our clinical practice, and some manufacturers have excluded it from their equipment.
The performance of helical CT requires more input from the physician and technologist than does conventional CT. In addition to the collimation, one must specify a table feed parameter. Some manufacturers refer to this parameter as the table increment per tube rotation, especially if scan times longer than 1 second are available; other manufacturers simply refer to it as the table speed, especially if only one scan time (1 second) is available. The operator must also choose the duration of the scan and the interval at which transaxial images will be reconstructed.

The choice of collimation is based largely on the organ of interest, with decisions made much as they are in conventional CT. Collimation of 2–3 mm is employed for small structures, such as lung nodules and renal arteries. Collimation of 5 mm is commonly used in the neck and abdomen, and 8–10-mm collimation is used routinely in the chest. The table increment is generally set equal to the collimation (pitch = 1). However, one may double the table increment relative to the collimation (pitch = 2), with some loss in longitudinal resolution (Fig 4).

We find it helpful to post a chart of reconstruction lengths achieved with different combinations of available collimation settings and table increment settings for our scanner (Fig 6). Such a chart serves to remind technologists and physicians of the options in choosing parameters for helical CT of a given volume. Our goal is to minimize the collimation to cover the volume of interest, and we accept a pitch up to 2, provided that 180° interpolation is employed. Thus, if we know the volume of interest is 15 cm in length, we can choose either 3- or 5-mm collimation matched with 5-mm table incrementation.

The total scan time depends on the scanner capabilities and the patient’s ability to hold his or her breath. If patients are unable to hold their breath beyond a certain duration, one should not exceed that value in performance of a helical CT examination. Some scanners are capable of performing only one preprogrammed helical scan. Others permit the performance of multiple preprogrammed helical scans such that two or three separate helical scans can be performed with a short breathing interval between scans (Fig 7). This is perhaps more advantageous in patients who cannot hold their breath for a prolonged period.

The choice of the reconstruction interval also depends on several factors. There is a trade-off between practical issues, such as processing time,
was employed rather than contiguous transaxial images. Their confidence was also increased when a 50% overlap was used, as 33% more lesions were identified as “definite” and the number of “probable” or “possible” lesions decreased by 23% and 44%, respectively. The value of overlapping sections is illustrated in Figure 8. In contiguous transaxial imaging, a small lesion centered between two contiguous sections is poorly visualized because of volume averaging. When the reconstruction interval is chosen to be one-half of the collimation (50% overlap), the same lesion may fall within the center of an overlapping section and its relative conspicuity is increased.

If a 50% overlap is beneficial for detecting small lesions, would a greater overlap (eg, 80% or 90%) provide additional benefit? This question was addressed in a theoretic study of the influence of reconstruction interval on longitudinal resolution (Fig 9) (14). (In this study, the section-sensitivity profiles and transfer functions were derived for conventional and helical CT. For helical CT with 180° linear interpolation, the section-sensitivity profile was computed as the convolution of the detector response, table motion, and low-pass filtering functions. Since the bandwidth of the transfer function is inversely proportional to the sharpness of the section-sensitivity profile, longitudinal resolution was approximated as one-half the reciprocal of the one-tenth cutoff frequency of the transfer function.) To examine the question here, consider three CT studies performed with 5-mm collimation: conventional CT, helical CT with a pitch of 1, and helical CT with a pitch of 2. For reconstruction intervals exceeding the collimation, longitudinal resolution is equal to the reconstruction interval. When images overlap by 20% (section interval of 4 mm), longitudinal resolution is still given by the reconstruction interval. Decreasing the reconstruction interval to smaller values with greater degrees of overlap provides no improvement in longitudinal resolu-
tion for a helical CT study with a pitch of 2. However, for a helical CT study with a pitch of 1, this plateau does not occur until a 40% overlap (3-mm reconstruction interval) is reached. For a conventional CT study, longitudinal resolution is slightly improved beyond that achieved with helical CT with a pitch of 1; its plateau occurs at a 60% overlap (2-mm section interval).

However, for a given x-ray dose, helical CT allows substantially better longitudinal resolution than does conventional CT because of its inherent retrospective reconstruction capability. Based on these simulations, we recommend reconstructing one to two sections per table increment for routine diagnosis and at least three sections per table increment for multidimensional imaging.

STAIR-STEP ARTIFACT

A processing artifact unique to helical CT is the "stair-step" artifact (15). The artifact is most apparent on inclined surfaces in longitudinal reformatted and three-dimensional images (Fig 10). We first observed it in images of aluminum ramp phantoms used to define the section profile in conventional CT. When a multiplanar reformation is performed, the ramps should appear as thin, oblique lines. However, with reformations from helical CT images, they are depicted as steps rather than as straight lines. The longitudinal height of the step is proportional to the table increment and independent of the collimation or reconstruction interval (Fig 11).

Although the phenomenon has the same appearance as aliasing caused by undersampling, it is a distinct artifact that results from the interpolation process. The stair-step appearance is largely caused by aliasing when the reconstruction interval is large and the table increment is small (relative to the size of the feature). If the reconstruction interval is much less than the collimation, as is common practice for multiplanar and three-dimensional imaging, the interpolation artifact predominates. The artifact results from inconvenient interpolation geometry associated with high-contrast interfaces aligned oblique to the direction of table motion (16). The artifact is most apparent in images of narrow structures of high contrast and obtained with high zoom. The artifact is also worse in images of oblique surfaces that are nearly parallel to the transverse plane, as opposed to oblique surfaces that are nearly orthogonal to the transverse plane.

Figure 10. Coronal maximum intensity projection from a helical CT scan (3-mm collimation, 5-mm table increment, 1-mm reconstruction interval) of the iliac arteries demonstrates a stair-step artifact. The stair-step artifact is seen as discontinuities along the arteries oriented oblique to the direction of patient travel. The artifact is more pronounced when the artery is nearly parallel to the transverse plane and is less pronounced when the artery is nearly orthogonal to the transverse plane.

SUMMARY

The performance of helical CT requires several user-defined parameters that exceed the requirements of conventional CT. One needs to carefully select the collimation, table increment, and reconstruction interval. Minimizing these parameters maximizes longitudinal resolution but with various trade-offs. Decreasing the collimation decreases the effective section thickness but increases pixel noise. Limiting the table increment to a pitch of 1 limits the broadening of the effective section thickness associated with the helical technique but also limits the coverage that can be achieved with a given helical scan. Our general practice is to minimize the collimation to cover the volume of interest and to accept a pitch up to 2, provided that we are using 180° interpolation. The reconstruction interval is also minimized to maximize longitudinal resolution but with trade-offs of increased image processing time, data storage requirements, and physician time for image review. For routine diagnosis, we recommend reconstruction of one to two sections per table increment, and, for multiplanar and three-dimensional imaging, we recommend at least three sections be reconstructed per table increment. The scan duration is dictated by both patient and machine factors.

REFERENCES

Figure 11. (a) Longitudinal reformatted images from helical CT (8-mm collimation, 8- and 16-mm table increment [middle and right, respectively], 1-mm reconstruction interval) of thin aluminum plates oriented oblique (45°) to the direction of patient travel demonstrate stair-step artifacts. These plates should appear as straight lines in ideal reformatted images (left) but instead appear as discontinuous surfaces (middle, right). The height of the stair-step is proportional to the table increment. (b) Source transaxial helical CT images obtained with a 16-mm table increment reveal asymmetry to the depiction of the aluminum plates in cross-section, which depends on table position. The blur about the leading and trailing edges of the plate is symmetric at 0, 8, and 16 mm. The blur is skewed toward the leading edge of the plate at 3 mm and toward the trailing edge at 11 mm. Thus, the spatial period of this artifact is equal to the table increment. The artifact results from inconvenient interpolation geometry associated with high-contrast interfaces that are obliquely aligned to the direction of patient travel.