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Optimal Section Spacing in Single-Detector Helical CT[1]

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Abbreviations:
EST = effective section thickness
FWHM = full width at half maximum

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To define the section spacing that maximizes longitudinal resolution without needless section overlap, the optimal percentage of overlap was computed theoretically and expressed as a constant relative to the effective section thickness. For imaging applications that require maximal longitudinal resolution, single-detector helical computed tomographic images should be reconstructed with at least 60% overlap relative to the effective section thickness.

On a single helical computed tomographic (CT) scan, the number of reconstructed sections is limitless such that hundreds of overlapping transverse images may be reconstructed with a small section increment. Urban et al (1) reported a 10% increase in liver lesion detection when images were reconstructed with 50% overlap. However, if 50% overlap is valuable, what about higher degrees of overlap such as 80% or 90%? Even subtle excess in section overlap can lead to substantial costs associated with the time to reconstruct the images and the resources needed to store the images.

For three-dimensional imaging applications, investigators (2) conclude empirically that images should be reconstructed with at least 50% overlap. On the basis of qualitative assessment of three-dimensional rendering in a CT colonographic application, we previously reported that transverse images should be reconstructed with at least 60% overlap (relative to the effective section thickness [EST]) (3). These results are difficult to compare with previous theoretic estimates for section spacing that were made with the Nyquist sampling criterion. Specifically, Wang and Vannier (4) report the section spacing that satisfies the Nyquist sampling criterion is the number of reconstructed sections per collimation as a function of pitch (Table 1). However, most radiologists find it difficult to remember or use such a complex relationship when they specify helical CT protocols.

Our purpose was to simplify determination of the optimal section spacing for single-detector helical CT protocols. We sought to define the optimal section spacing in terms of the EST theoretically and thereby justify our previous empiric determination of the optimal section spacing in a three-dimensional imaging application (3).

Materials and Methods

We applied the previously defined theoretic relationship between optimal section spacing (expressed as the number of sections per collimation) and pitch to the standard descriptor of the EST as measured by Polacin et al (5), full width at half maximum (FWHM) of the section sensitivity profile. Polacin et al report that the EST is unchanged at a pitch of 1.0 relative to conventional scanning and is increased by 30% at a pitch of 2.0. They also found a linear relationship at intermediate pitches between 1.0 and 2.0. Thus, we computed the percentage of overlap relative to the collimation and the percentage of overlap relative to EST on the basis of the relationship between the number of sections per collimation and pitch described by Wang and Vannier (4) (Table 1).

We next approached this problem from a theoretic standpoint whereby the section sensitivity profile was presumed to be Gaussian, and the EST was estimated from the collimation and table increment (Appendix). Theoretic estimates of the FWHM, full width at 10th maximum, and full width at 10th area of the section sensitivity profile for helical CT with 5.0-mm collimation and pitch of 2.0 were compared with similar empiric measures from Polacin et al (5), and the percentage of error was calculated. Mathematic analysis was carried further, and the optimal percentage of overlap was expressed as a constant relative to the EST.

TABLE 1
Recommended Number of Reconstructed Sections per Collimation

Pitch	Sections per Collimation	Percentage of Overlap*
0.1	3.30	70
0.3	3.12	68
0.5	3.12	68
0.7	2.97	66
0.9	2.79	64
1.1	2.61	62
1.3	2.44	59
1.5	2.27	56
1.7	2.12	53
1.9	1.98	49

Note.—Reprinted, with permission, from reference 4.
* Relative to collimation.

TABLE 2
Computation of Percentage of Overlap Relative to EST at Helical CT

Collimation and Pitch	EST (mm)*	No. of Sections per Collimation†	Section Spacing (mm)	Percentage of Overlap: Relative to Collimation‡	Percentage of Overlap: Relative to EST§
5.0 mm					
1.00	5.00	2.70	1.85	63	63
1.10	5.15	2.60	1.92	62	63
1.20	5.30	2.50	2.00	60	62
1.30	5.45	2.45	2.04	59	63
1.40	5.60	2.35	2.13	57	62
1.50	5.75	2.30	2.17	57	62
1.60	5.90	2.20	2.27	55	61
1.70	6.05	2.10	2.38	52	61
1.80	6.20	2.05	2.44	51	61
1.90	6.35	2.00	2.50	50	61
2.00	6.50	1.95	2.56	49	61
3.0 mm					
1.00	3.00	2.70	1.11	63	63
1.10	3.09	2.60	1.15	62	63
1.20	3.18	2.50	1.20	60	62
1.30	3.27	2.45	1.22	59	63
1.40	3.36	2.35	1.28	57	62
1.50	3.45	2.30	1.30	57	62
1.60	3.54	2.20	1.36	55	61
1.70	3.63	2.10	1.43	52	61
1.80	3.72	2.05	1.46	51	61
1.90	3.81	2.00	1.50	50	61
2.00	3.90	1.95	1.54	49	61

Note.—Computation based on the criteria for the optimal number of reconstructed sections per collimation in Table 1.
* Calculated, as in Polacin et al (5), as FWHM of the section sensitivity profile.
† From Table 1.
‡ Calculated as [(collimation − section spacing)/collimation] × 100.
§ Calculated as [(EST − section spacing)/EST] × 100.

Results

The percentage of overlap relative to the collimation and the percentage of overlap relative to EST for pitch settings between 1.0 and 2.0 are illustrated in Table 2 for 5.0- and 3.0-mm collimations on the basis of the relationship between the number of sections per collimation and pitch described by Wang and Vannier (4) (Table 1). The optimal percentage of overlap expressed relative to the collimation ranged from 63% to 49% for pitch values ranging from 1.0 to 2.0. However, the optimal percentage of overlap expressed relative to the EST ranged from 63% to 61% for pitch values ranging from 1.0 to 2.0, independent of collimation.

When estimated theoretically, presuming the section sensitivity profile to be Gaussian (Appendix), increasing the pitch from 1.0 to 2.0 increases the EST by the square root of two. When applied to EST data for helical CT scans obtained with 5.0-mm collimation, the percentage of error between empiric and theoretic measures of the FWHM was found to be 3% and 9% for pitch settings of 1.5 and 2.0, respectively (Table 3). However, the percentage of error for other metrics of the section sensitivity profile (full width at 10th maximum and full width at 10th area) were quite small, ranging from 0% to 2%.

When carried further mathematically, the optimal section spacing, defined as the number of sections per collimation, was reexpressed as the percentage of overlap relative to the EST: [(EST − section spacing)/EST] × 100. The optimal percentage of overlap, computed in this fashion, was found to be 63%.

Discussion

With helical CT, the EST is inherently broadened. Thus, with consideration of EST alone, helical CT with full-scan interpolation resulted in worsened longitudinal resolution relative to conventional scanning (6). Advances in the interpolation algorithms used to estimate data for transverse image reconstruction minimized this effect such that, for a pitch of 1.0, no appreciable increase in EST (FWHM) was seen with helical CT (5). With this benefit, investigators began increasing pitch as the pitch-related increase in EST was less prohibitive with half-scan than with full-scan interpolation algorithms. This loss of resolution owing to broadening of the section sensitive profile is compensated by the ability to reconstruct images retrospectively with a high degree of overlap. With overlapping image reconstruction, the longitudinal resolution that may be achieved with helical CT approaches a theoretic maximum (7). The section spacing required to maximize longitudinal resolution without needless section overlap was the topic of this investigation.

The optimal section spacing may be loosely expressed as reconstruction of two to three sections per collimation. Although the difference between two and three sections per collimation may not be apparent in routine clinical applications, specialized applications may reveal differences in the conspicuity of small structures and the magnitude of artifacts present on three-dimensional renderings. In addition, there is a large difference between two and three sections per collimation in terms of the processing time required to reconstruct these sections and the physical memory required to store these images for three-dimensional rendering. Thus, we wished to reconstruct sections with the least amount of overlap required to achieve maximum longitudinal resolution without needless section overlap and to develop a simple but precise means of describing the optimal section spacing.

In specifying protocols for helical CT examinations, radiologists commonly recall the relationship between EST and pitch described by Polacin et al (5). With half-scan interpolation, remembering that the EST (FWHM) is unchanged with a

TABLE 3
Validation of Formula for Estimation of Section Thickness With Half-Scan Interpolation

Parameters and EST	FWHM (mm)	Full Width at 10th Maximum (mm)	Full Width at 10th Area (mm)
Collimation, 5.0 mm; pitch, 2.0			
Measured (pitch = 1.0)	5.0	8.0	5.90
Measured (pitch = 2.0)	6.5	11.3	8.40
Predicted (pitch = 2.0)	7.1	11.3	8.34
Percentage of error	9	0	1
Collimation, 5.0 mm; pitch, 1.5			
Measured (pitch = 1.0)	5.00	8.00	5.90
Measured (pitch = 1.5)	5.75	9.65	7.15
Predicted (pitch = 1.5)	5.95	9.52	7.02
Percentage of error	3	1	2

Note.—Measured values are taken from Polacin et al (5).

TABLE 4
Common Helical CT Techniques

Technique*	EST (FWHM) (mm)	Percentage of Overlap Relative to EST
3.0 × 2.0 × 1.5	3.9	62
5.0 × 1.6 × 2.0	5.9	66
5.0 × 2.0 × 2.5	6.5	62

* Collimation (mm) × pitch × reconstruction interval (mm).

pitch of 1.0 and increases linearly by 30% with a pitch of 2.0 (compared with conventional scanning), computation of the EST is simple. Thus, radiologists easily recall that 5.0-mm collimation with a pitch of 2.0 results in an EST of 6.5 mm. Similarly, 3.0-mm collimation with a pitch of 2.0 results in an EST of 3.9 mm.

What is not so easily remembered is the reconstruction interval necessary to achieve maximal longitudinal resolution as expressed in Table 1. On the basis of our previous empiric determination (3) and the theoretic predictions of this study, radiologists can now remember that images should be reconstructed with at least 60% overlap relative to the EST. Thus, for 5.0-mm collimation and a pitch of 2.0, the EST (FWHM) is increased by 30% (6.5 mm), and images should be reconstructed with a reconstruction interval of 2.5 mm. This results in a percentage of overlap of 62% relative to the EST: [(6.5 − 2.5)/6.5] × 100. Table 4 lists some commonly employed helical CT techniques which satisfy this criterion. Given the predictable increase in EST with single-detector helical CT with use of half-scan interpolation, the optimal percentage of overlap relative to the collimation may be expressed as decreasing from approximately 60% to 50% as pitch is increased from 1.0 to 2.0 (Table 2), thus obviating recall of the specific increase in EST for such scanners.

These results are applicable to single-detector helical CT. Early results with multidetector helical CT suggest that pitch-related section profile broadening is not as severe with multidetector as with single-detector scanners (8–10), and longitudinal resolution may be maximized with images that are reconstructed with slightly less overlap (11). Further work will be required to determine the optimal section spacing with multidetector helical CT.

Thus, specification of scanning protocols for single-detector helical CT can be simplified by remembering two facts. First, the EST is broadened by 30% with an increase of pitch from 1.0 to 2.0. Second, to maximize longitudinal resolution without needless section overlap, images should be reconstructed with 60% overlap relative to the EST.

Appendix

Number of Reconstructed Sections per Collimation

It has been shown that the SD σ of the section sensitivity profile can be computed as follows (4):

$$\sigma = \sqrt{\frac{D^2}{12} + \frac{T^2}{24}},$$

where D and T are detector collimation and table feed, respectively. Because the section sensitivity profile is a Gaussian-like distribution, the SD Σ of the Fourier transform of the section sensitivity profile can be approximated as $1/2\pi\sigma$. Technically, the cutoff frequency $f_{\max}$ of the Fourier spectrum can be obtained by tripling Σ, that is, $f_{\max} = 3\Sigma$.

The area from −3 SDs to +3 SDs under a normal (Gaussian) probability density function curve is 99.7% of the total area. As a result, in statistical practice, any event outside of this range is typically considered unlikely (less than a chance of 0.3%). Because the section sensitivity profile is very similar to a Gaussian function in shape, its Fourier transform is also Gaussian-like. For these reasons, we chose the cutoff frequency to be 3 SDs.

Hence, the longitudinal sampling step Δ, which is the reconstruction interval between adjacent transverse sections, can be obtained by meeting the Nyquist sampling requirement:

$$\Delta = \frac{1}{2f_{\max}} = \frac{\pi}{3}\sqrt{\frac{D^2}{12} + \frac{T^2}{24}}.$$

In other words, the number n of reconstructed sections per collimation D is

$$n = \frac{3}{\pi\sqrt{\frac{1}{12} + \frac{p^2}{24}}},$$

where p denotes the pitch, defined as T/D.

EST(p)

The EST is a figure of merit used to measure the width of the section sensitivity profile, which is a function of the pitch p. The popular ESTs include the FWHM, the full width at 10th maximum (FWTM), and the full width at 10th area (FWTA). The following formula can be used to compute EST(p):

$$\text{EST}(p) = \frac{\sqrt{\frac{1}{12} + \frac{p^2}{24}}}{\sqrt{\frac{1}{12} + \frac{1}{24}}}\,\text{EST}(1)$$
$$= 2\sqrt{\frac{1}{6} + \frac{p^2}{12}}\,\text{EST}(1).$$

Clearly, when $p = 1$, we have the perfect result; the EST(1) should be prespecified or measured directly. The factor in front of EST(1) compensates for the pitch effect, with the rationale that a good section thickness measure should be proportional to the SD of the section sensitivity profile. In other words, the larger the SD of the section sensitivity profile, the thicker the sections. According to this generic EST(p) formula, FWHM(2), FWTM(2), and FWTA(2) can be predicted from FWHM(1), FWTM(1), and FWTA(1), respectively. The results of 5.0-mm collimation and pitch of 2.0 and 1.5 are listed in Table 3, which indicates the validity of our formula.

Number of Reconstructed Sections per EST

The percentage of overlap α(EST) can be expressed as

$$\alpha(\mathrm{EST}) = 1 - \frac{\Delta}{\mathrm{EST}(p)}$$

$$= 1 - \frac{\frac{\pi}{3}\sqrt{\frac{D^2}{12}+\frac{T^2}{24}}}{\frac{\sqrt{\frac{1}{12}+\frac{p^2}{24}}}{\sqrt{\frac{1}{12}+\frac{1}{24}}}\mathrm{EST}(1)}$$

$$= 1 - \frac{\pi}{3}\sqrt{\frac{1}{12}+\frac{1}{24}}\,\frac{D}{\mathrm{EST}(1)}$$

$$= 1 - \frac{\sqrt{2}\pi}{12}\,\frac{D}{\mathrm{EST}(1)}.$$

Because FWHM(1) = D, we immediately have $\alpha(\mathrm{FWHM}) = 1 - (\sqrt{2}\pi/12) = 0.63$.

Thus, these theoretic predictions indicate that sections should be reconstructed with at least 63% overlap relative to the EST.

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