Published in final edited form as:

Phys Med Biol. 2006 December 07; 51(23): 6199–6211. doi:10.1088/0031-9155/51/23/018.

An analytical algorithm for skew-slit collimator SPECT with uniform attenuation correction

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Abstract

To replace the conventional pinhole (normal cone-beam) collimator, a novel skew-slit collimator was previously proposed and a Novikov-type algorithm developed to reconstruct images using the skew-slit geometry. The goal of this paper is to develop a reconstruction algorithm that has better noise control than the Novikov-type algorithm. The new algorithm is able to compensate for uniform attenuation, and computer simulation results show that reconstructed images are less noisy.

1. Introduction

In single photon emission tomography (SPECT), the system detection sensitivity and spatial resolution are mainly determined by the collimator. The simple collimator routinely used in SPECT scans is the parallel-hole collimator. The image reconstruction algorithms with uniform attenuation correction for this parallel-beam geometry are well known (Bellini *et al* 1979, Tretiak and Metz 1980, Gullberg and Budinger 1981, Clough and Barrett 1983, Inouye *et al* 1989, Metz and Pan 1995) and an analytical image reconstruction algorithm with non-uniform attenuation correction for parallel-beam geometry was presented in Novikov (2002).

However, for small-object imaging, the parallel-hole collimator is not geometrically efficient. To achieve higher spatial resolution and sensitivity, convergent collimators such as cone-beam or pinhole collimators are used. For a given spatial resolution, the cone-beam collimator has a higher sensitivity than the pinhole collimator for larger objects, while the pinhole collimator has a higher sensitivity than the cone-beam collimator for smaller objects (Qi *et al* 2005). Therefore, the pinhole collimator is better for small-object SPECT imaging (Jaszczak *et al* 1994, Weber *et al* 1994, Ishizu *et al* 1995, Yukihiro *et al* 1996, Wu *et al* 2000, McElroy *et al* 2002, Beekman and Vastenhouw 2004, Meikle *et al* 2005). Another advantage of the pinhole collimator is that it is possible to make a multiple-pinhole collimator to provide increased sensitivity without sacrificing spatial resolution (Meikle *et al* 2003, Schramm *et al* 2003, Beekman *et al* 2005, Cao *et al* 2005).

The most common SPECT scanning trajectory is a planar orbit, for example, a circular orbit. Data acquired by using a circular orbit do not fully fill the Radon space for pinhole imaging, and the space without measured data in the Radon space forms two cones, which are often called ‘missing cones’ (Grangeat 1991). Therefore, the pinhole projection data are not sufficient for exact image reconstruction and axial artefacts are formed in the reconstructed image. In the pinhole geometry, the axial cone angle is the same as the transaxial cone angle and axial artefacts depend on the axial cone angle. Thus the larger the axial cone angle, the more severe the axial artefacts appear. On the other hand, the spatial resolution is determined by both the transaxial and axial cone angles. Axial artefacts are therefore more severe if higher spatial resolution is required for the pinhole collimator.

A skew-slit collimator, which is composed of a horizontal slit and a vertical slit, was proposed by our group (Huang and Zeng 2006), as a means to overcome this disadvantage. In this new geometry, the axial and transaxial cone angles are independent; thus, cone beams with a larger transaxial cone angle and smaller axial cone angle can be formed. Compared to the conventional cone-beam geometry, higher spatial resolution in the transaxial direction and fewer axial artefacts can be achieved simultaneously by the skew-slit geometry. To suppress the axial artefacts further, a multi-skew-slit collimator is proposed, which consists of a vertical slit followed by several horizontal slits with different axial positions. If the projections acquired through different horizontal slits do not overlap with each other, an image can be reconstructed from the projections acquired through every horizontal slit (Huang and Zeng 2006). Combination of the images can give an image with still less severe axial artefacts. If the projections acquired through different horizontal slits do overlap with each other, an iterative algorithm can be used to reconstruct images from the overlapped projections.

Our group developed an analytical algorithm with non-uniform attenuation correction for this skew-slit imaging geometry (Huang and Zeng 2006). The algorithm was developed by extending Novikov’s parallel-beam, non-uniform attenuation correction algorithm (Novikov 2002) to tilted fan-beam geometry and using FDK approximation (Feldkamp *et al* 1984). In this paper, we propose another analytical algorithm for this skew-slit imaging geometry but with uniform attenuation correction. This algorithm is extended from our former analytical algorithm for circular orbit cone-beam geometry (Tang *et al* 2005), which was developed from Metz and Pan’s quasi-optimal image reconstruction algorithm with uniformly attenuated parallel-beam data (Metz and Pan 1995). Thus, this algorithm is expected to have better noise properties, although it can only compensate for uniform attenuation. In fact, the attenuation coefficients in some organs such as the brain can often be approximated as uniform in practice.

2. System

There are two types of cone-beam imaging systems: the pinhole collimator system and the cone-beam collimator system. Both systems have an isotropic cone angle. Therefore, an increase in spatial resolution in the transaxial direction and a reduction in axial artefacts cannot be achieved at the same time. To achieve both in the same imaging system, the transaxial cone angle and the axial cone angle must be independent of each other. Like the

pinhole imaging principle, in a slit system, the image is magnified and inverted in the direction perpendicular to the slit. In a skew-slit system, two slits are positioned perpendicular to each other; one slit is horizontal and the other is vertical. Magnification of the image can thus be regulated independently in two orthogonal directions. Consequently, increased spatial resolution can be achieved in the transaxial direction simultaneously with a reduction of artefacts in the axial direction.

The skew-slit system is shown in figure 1. The skew-slit collimator consists of two tungsten plates, which are parallel to each other. The skew-slit collimator detector unit rotates around the object. The plate closer to the object has a vertical slit, that is, the slit is parallel to the axis of the detector rotation. The plate distal to the object has a horizontal slit. These two slits have distances F_1 and F_2 to the axis of rotation, respectively. The distance from the horizontal slit to the detector is denoted as D . The vertical and horizontal amplification factors are given as

$$\text{amplification_factor (vertical)} = \frac{D}{F_2}, \quad (1)$$

$$\text{amplification_factor (horizontal)} = \frac{D + (F_2 - F_1)}{F_1}. \quad (2)$$

Equations (1) and (2) show that the image amplification factors in the vertical (i.e. axial) and horizontal (i.e. transaxial) directions are independent. The amplification factors can be adjusted independently by changing the distances F_1 and F_2 . The image amplification factor in the horizontal direction is greater than the image amplification factor in the vertical direction if $F_2 > F_1$. The projection rays projecting on the detector with the same vertical position pass through the horizontal slit and focus on a point at the vertical slit, while the projection rays projecting on the detector with the same horizontal position pass through the vertical slit and focus on a point at the horizontal slit (see figure 2). Therefore, the projection rays of the skew-slit system are composed of a series of fan beams, and their focal points are located on the slits. When $F_1 = F_2$, the two orthogonal focal lines (vertical and horizontal slits) become a focal point and the skew-slit system degenerates into a pinhole system.

Similar to a cone-beam system, the projection data from a skew-slit system are not sufficient to provide an artefact-free reconstruction if the detector rotates in a planar orbit. However, in the Radon space the ‘missing cone’ for the skew-slit geometry is smaller than that in a pinhole geometry if the pinhole is located at the vertical slit position.

When a smaller amplification factor in the vertical direction is used in a skew-slit system, a large area of the detector in the vertical direction is unused for projection data acquisition. To fully utilize the large area detector, the single horizontal slit is replaced by several horizontal slits. The number of horizontal slits is determined by the vertical amplification factor. Figure 3 illustrates such a skew-slit system, which has three horizontal slits. In this system, three sets of projections can be acquired through the three horizontal slits. The three

sets of projections can reduce the ‘missing cone’ in the Radon space. This setup also increases the counts acquired and thus has better noise properties than the skew-slit system.

3. Algorithm

This paper proposes an algorithm for the skew-slit imaging geometry in the form of a backprojection and filtering. The data are first backprojected into a 3D image volume along the projection rays without an exponential factor; then slice-by-slice filtering is performed using our previously developed algorithm (Tang *et al* 2005). This algorithm is expected to have better noise properties than the algorithm previously proposed in Huang and Zeng (2006).

Let the 3D activity distribution function in the cylindrical coordinates be $f(r, \phi, z)$, and the projections acquired by this skew-slit system be $q(s, z, \beta)$. Here β is the view angle, s and z are the two coordinates of the projections on the detector plane, respectively. Variables r, ϕ, s, z and β are described in figure 4. We have $x = r \cos \phi$ and $y = r \sin \phi$. Then the modified attenuated projections (i.e. the exponential Radon transform) are $m(s, z, \beta)$ with

$$m(s, z, \beta) = q(s, z, \beta) e^{\mu D(s, z, \beta)}, \quad (3)$$

where $D(s, z, \beta)$ is the distance shown in figure 5 and μ is the linear attenuation coefficient of the convex attenuator.

The reconstruction steps are as follows.

Step 1. Modify the projection data by an exponential factor $e^{\mu D}$, obtaining $m(s, z, \beta)$.

Step 2. Backproject the projections $m(s, z, \beta)$ along the projection rays, obtaining a 3D volume $b(r, \phi, z)$ in the cylindrical coordinates (see figure 5),

$$b(r, \phi, z) = \int_0^{2\pi} m(s, z_0, \beta) \left| \begin{array}{l} z_0 = -zD/(F_2 + r \cos(\phi - \beta)) \\ s = -rR \sin(\phi - \beta)/(F_1 + r \cos(\phi - \beta)) \end{array} \right| \frac{R_{\text{slit}} \cos \sigma}{K_{\text{slit}}} d\beta, \quad (4)$$

where

$$R = D + F_2 - F_1, \quad (5)$$

$$K = \sqrt{R^2 + s^2} - r \sin(\sigma_0 + \beta - \phi), \quad (6)$$

$$K_{\text{slit}} = \sqrt{K^2 + z^2}, \quad (7)$$

$$R_{\text{slit}} = \sqrt{z^2 + D^2} + \sqrt{\left(\frac{z(F_2 - F_1)}{D}\right)^2 + (F_2 - F_1)^2}, \quad (8)$$

$$\sigma = \tan^{-1} \left(\frac{r \cos(\beta + \pi - \phi)}{R_{\text{slit}}} \right). \quad (9)$$

Step 3. Perform the Hankel transform and Fourier transform of $b(r, \phi, z)$ slice-by-slice for every fixed z , obtaining $B_k(\omega, z)$ for each slice z .

$$B_k(\omega, z) = (-i)^k \int_{\phi=0}^{2\pi} \int_{r=0}^{\infty} b(r, \phi, z) e^{-ik\phi} J_k(2\pi\omega r) r dr d\phi. \quad (10)$$

Step 4. Use a generalized central-slice theorem (Tang *et al* 2005) to multiply $B_k(\omega, z)$ by the ramp filter $|\omega|$ and perform a frequency shift for each slice z (note that the frequency shift is to compensate for the attenuation effect):

$$F_k(\omega, z) = \frac{[\gamma(\omega_\mu)]^k}{[\gamma(\omega_\mu)]^{2k} + 1} |\omega_\mu| B_k(\omega_\mu, z), \quad (11)$$

where

$$\gamma(\omega_\mu) = \frac{\sqrt{\omega_\mu^2 - (\mu/2\pi)^2}}{\omega_\mu + \mu/2\pi} \quad \text{and} \quad \omega_\mu = \sqrt{\omega^2 + (\mu/2\pi)^2}. \quad (12)$$

Step 5. Perform the inverse Hankel transform and inverse Fourier transform of $A_k(\omega, z)$. The activity image $a(r, \phi, z)$ is obtained as

$$f(r, \phi, z) = 2\pi \sum_{k=-\infty}^{\infty} i^k \int_{\omega=0}^{\infty} A_k(\omega, z) e^{ik\phi} J_k(2\pi\omega r) \omega d\omega, \quad (13)$$

and the image in the Cartesian system $a(x, y, z)$ can be obtained as

$$f(x, y, z) = 2\pi \sum_{k=-\infty}^{\infty} i^k \int_{\omega=0}^{\infty} A_k(\omega, z) e^{ik \tan^{-1}(y/x)} J_k(2\pi\omega \sqrt{x^2 + y^2}) \omega d\omega. \quad (14)$$

The above algorithm is the same as that developed in Tang *et al* (2005), except the backprojection procedure in step 1.

4. Simulation results

In our computer simulation studies, the projection data were generated analytically from the 3D modified Shepp–Logan phantom with a uniform attenuator (see table 1). The uniform attenuator in the simulations had the same spherical shape as the exterior of the modified Shepp–Logan phantom and a linear attenuation coefficient of 0.05 unit^{-1} . This value is approximately the attenuation coefficient of water at 140 keV when one unit is 3.6 mm. A unit is the detector bin size.

The parameters D , F_1 and F_2 of the skew-slit system were 130, 50 and 90 units, respectively. The vertical positions of the three horizontal slits were 24, 0 and -24 units, respectively. Attenuated skew-slit projection data without noise were generated analytically by this skew-slit imaging system with 120 views over 360° . There were 257×257 projection samples in the detector plane.

4.1. Axial artefacts comparison

For comparison purposes, projection data were also acquired from a pinhole system, which was derived from the skew-slit system by setting $F_2 = F_1 = 50$ units and keeping other parameters the same.

Figure 6 shows reconstructed images from the pinhole projections, skew-slit projections and multi-skew-slit projections. All projection data were noiseless. The pinhole system and skew-slit system had the same horizontal amplification factor of 3.4, but different vertical amplification factors of 3.4 and 1.4, respectively. Therefore, these two systems had the same transaxial spatial resolution, but different axial artefacts.

Figure 6 shows the three central cross-sectional images of the 3D reconstructions for each acquisition system. We can see that the axial artefacts generated by the skew-slit system are much less severe than those of the pinhole system and more severe than those of the multi-skew-slit system. That is, the skew-slit system reduces the axial artefacts by decreasing the vertical amplification factor, and the multi-skew-slit system further reduces the axial artefacts, which is due to the decreased ‘missing cone’ in the Radon domain.

4.2. Resolution comparison

For comparison purposes, projection data were also acquired from a different pinhole system, which was degenerated from the skew-slit system by setting $F_2 = F_1 = 90$ and keeping other parameters the same. A different resolution phantom was used.

This new pinhole system and skew-slit system had the same vertical amplification factor of 1.4, but different horizontal amplification factors, which were 1.4 and 3.4, respectively. Therefore, the axial artefacts of these two systems were approximately the same, while the skew-slit system had a better transaxial spatial resolution. Images in figure 7 are

reconstructed from the new pinhole projections and skew-slit projections. The skew-slit has a better transaxial spatial resolution than the pinhole system if axial artefacts are the same.

4.3. Noise property comparison

Before comparing the noise properties of the proposed algorithm and the Novikov-type algorithm (Huang and Zeng 2006), the two algorithms were compared for spatial resolution. Images reconstructed by the proposed algorithm from noise-free skew-slit and multi-skew-slit projection data are shown in figure 6. Figure 8 then just shows the images reconstructed by the Novikov-type algorithm from noise-free skew-slit and multi-skew-slit projection data. The peaks selected to compare the full width at half-maximum (FWHM) are shown in figure 8. The FWHMs of the peaks are listed in table 2. It is evident that these two algorithms have almost the same transaxial spatial resolution.

To compare the noise properties of the proposed algorithm and the Novikov-type algorithm, Poisson noise was added into the projections. Images were reconstructed by the proposed algorithm and the Novikov-type algorithm from the noisy skew-slit projection data. The data were from a one-horizontal-slit system. The noise properties of these two algorithms are compared in figure 9. Because the phantom was not uniform, we selected a uniform region to calculate the standard deviation. The selected region was a sphere with radius 7 and its centre located at $x = -16$, $y = 0$ and $z = 0$. For this particular study, the standard deviation of the proposed algorithm was 0.21, while the standard deviation of the Novikov-type algorithm was 0.31.

To further compare the noise properties of the proposed algorithm and the Novikov-type algorithm as well as to compare the noise properties of the skew-slit system and multi-skew-slit system, images were also reconstructed by the proposed algorithm and the Novikov-type algorithm from the noisy multi-skew-slit projection data. These are shown in figure 10. In the same selected region as in figure 9, the standard deviation of the noise with the proposed algorithm is 0.14, while the standard deviation of the noise with the Novikov-type algorithm is 0.18. It is evident that the proposed algorithm has better noise properties than the Novikov-type algorithm, and the multi-skew-slit system has better noise properties than the skew-slit system. Table 2 shows noise standard deviation values.

5. Conclusions

An analytical image reconstruction algorithm is presented for the skew-slit imaging system. The algorithm is able to compensate for uniform attenuation. Simulation results demonstrate that the skew-slit imaging geometry can simultaneously obtain higher spatial resolution in the transaxial direction and fewer axial artefacts than the conventional pinhole geometry. The multi-skew-slit system can reduce the ‘missing cone’ in the Radon space, and the axial artefacts are further suppressed. The multi-skew-slit system also increases the detection photon counts, and has better noise properties than the system with only one horizontal slit.

To date, iterative reconstruction is the only way to reconstruct multi-pinhole images. The proposed multi-skew-slit system allows the use of a more efficient analytical algorithm to reconstruct the images. On one hand, an iterative algorithm provides more accurate

reconstructions by modelling the statistics, geometric response and scatter. On the other hand, an analytical algorithm is often more efficient than an iterative algorithm. In the special case where the projections acquired through different horizontal slits overlap with each other, an iterative algorithm should be used to reconstruct images from the overlapped projections, because the proposed analytical algorithm does not apply.

Novikov's algorithm is a filtered backprojection algorithm. Its backprojection contains an exponential weighting factor, which magnifies the noise. Kunyansky (2001) proved that the Tretiak–Metz inversion formula (Tretiak and Metz 1980) is a particular case of the Novikov formula, when the attenuator is a disk and the linear attenuation coefficient is a constant. The proposed algorithm, which does not use an exponential weighting factor in the backprojection, is based on Metz and Pan's quasi-optimal algorithm (Metz and Pan 1995) which has better noise properties than the Tretiak–Metz algorithm (Tretiak and Metz 1980). Therefore, the proposed algorithm has better noise properties than the Novikov-type algorithm (Huang and Zeng 2006). However, rigorous noise assessment is planned for future investigation and verification.

The proposed algorithm is an extension of our analytical image reconstruction algorithm (Tang *et al* 2005) from the cone-beam system to the skew-slit system. Simulation results show that this algorithm has better noise properties than the Novikov-type algorithm presented in Huang and Zeng (2006). However, the proposed algorithm only compensates for uniform attenuation while the Novikov-type algorithm compensates for non-uniform attenuation.

Acknowledgments

We thank Dr Roy Rowley for English editing.

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Figure 1.

A skew-slit collimator consists of two tungsten plates. Each plate contains a slit. The two slits are orthogonal to each other.

Figure 2.
Each slit consists of focal points of the projection rays.

Figure 3.
Illustration of a multi-skew-slit system.

Figure 4.
Illustration of the skew-slit backprojection geometry.

Figure 5.
Illustration of the boundary factor D .

Figure 6.

Reconstructed images. The first row shows the true phantom, the second row shows the images reconstructed from the pinhole system, the third row shows the images reconstructed from the skew-slit system and the last row shows the images reconstructed from the multi-skew-slit system. The left column shows the transaxial central-slice (i.e. the orbit plane) images. The middle and right columns show the two orthogonal central-slice images perpendicular to the trajectory.

Figure 7.

Reconstructed images. The first row shows the true phantom, the second row shows the images reconstructed from the pinhole system, the third row shows the images reconstructed from the skew-slit system and the fourth row shows the images reconstructed from the multi-skew-slit system. The left column shows the central-slice images parallel to the trajectory. The middle and right columns show the two orthogonal central-slice images perpendicular to the trajectory.

Figure 8.

Images reconstructed from noise-free projections. The images of the first row were reconstructed from skew-slit noise-free projections by the Novikov-type algorithm in Huang and Zeng (2006), and the images of the second row were reconstructed from the multi-skew-slit noise-free projection by the Novikov-type algorithm. The images of the first column are the $z = 0$ slice, the images of the second column and the third column are the $x = 0$ and $y = 0$ slices, respectively.

Figure 9.

Images reconstructed from noisy skew-slit projections. The images in the first row were reconstructed by the Novikov-type algorithm in Huang and Zeng (2006) from skew-slit noisy projections, and the images in the second row were reconstructed by the proposed algorithm from the same skew-slit noisy projections. The images of the first column are the $z = 0$ slice, the images of the second column and the third column are the $x = 0$ and $y = 0$ slices, respectively. The white circles show the sampled region for standard deviation calculation.

Figure 10.

Images reconstructed from noisy multi-skew-slit projections. The images in the first row were reconstructed by the Novikov-type algorithm in Huang and Zeng (2006) from multi-skew-slit noisy projections, and the images in the second row were reconstructed by the proposed algorithm from the same multi-skew-slit noisy projections. The images of the first column are the $z=0$ slice, the images of the second column and the third column are the $x=0$ and $y=0$ slices, respectively. The white circles show the sampled region for standard deviation calculation.

Parameters of the 3D modified Shepp–Logan phantom used in our numerical simulation. Here, x , y and z are the coordinates of the centre of the ellipse, a , b and c are the major and minor axes of the ellipse, respectively, and θ , ϕ and γ are three Euler angles.

Table 1

Phantom	x	y	z	a	b	c	θ	ϕ	γ	Density
	0.00	0.00	0.00	20.00	20.00	20.00	0.00	0.00	90.00	2.00
	0.00	0.00	0.00	19.00	19.00	19.00	0.00	0.00	90.00	-1.00
	4.40	0.00	0.00	6.20	2.20	9.00	0.00	0.00	72.00	-0.50
	-4.40	0.00	0.00	8.20	3.20	12.00	0.00	0.00	108.00	-0.50
	0.00	7.00	0.00	5.00	4.06	8.00	0.00	0.00	90.00	-0.50
	0.00	2.00	0.00	0.92	0.96	8.12	72.00	0.00	0.00	1.00
	0.00	-2.00	0.00	0.92	0.96	8.12	108.00	0.00	0.00	1.00
	-1.60	-8.1	8.00	5.06	4.06	3.06	108.00	45.00	0.00	-1.00
	0.00	-12.1	0.00	0.46	0.46	2.06	72.00	0.00	0.00	1.00
	1.20	-8.1	-8.00	5.06	4.06	3.06	45.00	45.00	90.00	1.00

Table 2

Resolution and noise property results of the Novikov-type algorithm and the proposed algorithm.

	The Novikov-type algorithm		The proposed algorithm	
	Skew-slit system	Multi-skew-slit system	Skew-slit system	Multi-skew-slit system
Resolution (FWHM)	0.52	0.53	0.49	0.51
Standard deviation	0.31	0.18	0.21	0.14