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14. ABSTRACT The goal of this research is to obtain systematic understandings of the effects of various physical factors that are important in breast tomosynthesis imaging and to develop techniques for effectively dealing with their effects and for reducing radiation dose. During the second year of the project we have achieved fruitful results based upon the progress made in our first year of the project. Specifically, we have further investigated the performance of the total-variation (TV) based algorithm under different data conditions and different constraint parameters. Furthermore, we have also proposed and investigated a new tomosynthesis imaging method with non-planar trajectories for yielding more data information with the same amount of imaging dose. We have also simulated the scatter in tomosynthesis breast imaging by convolving the ideal projection data with angular dependent scatter kernel.					
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INTRODUCTION

Breast tomosynthesis as a promising 3D imaging modality has the potential to overcome the major limitation of conventional mammography [1,2,3]. The loss of information in 2D projection imaging can be recovered in tomosynthesis imaging. Although considerable progress has been made in the last several years, improvements to several areas of breast tomosynthesis technology are still needed before it becomes suitable for routine clinical use. The goal of this research is to obtain systematic understandings of the effects of various physical factors that are important in breast tomosynthesis imaging and to develop techniques for effectively dealing with their effects and for reducing radiation dose. During the second year of the project we have conducted fruitful studies based upon the progress made in our first year of the project. Specifically, we have investigated the performance of the total-variation (TV) based algorithm under different data conditions and different constraint parameters. We have also proposed and investigated a new tomosynthesis imaging method with non-planar trajectories for yielding more data information with the same amount of imaging dose. Furthermore, we have investigated the scatter in tomosynthesis breast imaging by considering angular dependent scatter kernels.

1 Research Accomplishments

1.1 Investigation of reconstruction algorithms for breast tomosynthesis

In the first-year report, we have reported our progress on the performance of the TV-based algorithm when applied to tomosynthesis data generated from discrete images. The result in the study provides us the upper bound on the performance of the TV-based algorithm. During the last year, we continued to investigate the performance of the TV-based algorithm for the data contain data errors such as continuous-to-discrete inconsistency.

The TV-based algorithm that we have investigated seeks to find the solution for the optimization problem below [4]:

$$\vec{f}^* = \operatorname{argmin} ||\vec{f}||_{TV}, \tag{1}$$

with two constraints,

$$|M\vec{f} - \vec{g}| \leq \epsilon \quad \text{and} \quad f_i \geq 0,$$

where $\vec{f}^*$ is the reconstructed image and M is the linear operator representing the cone-beam forward projection in breast tomosynthesis. The inequality used in the first constraint accounts for data inconsistency, such as noise, continuous-to-discrete inconsistency, etc. The parameter ϵ can be selected for controlling the impact level of potential data inconsistency on the image reconstruction. Different constraint parameter ϵ yields the image with different image quality. Therefore, selection of a proper constraint parameter ϵ is important to achieve a good reconstruction.

In the last several months, we have investigated systematically the performance of the TV-based algorithm with different constraint parameter ϵ . Such investigative studies are illustrated by use of the example below. In the example study, a 2D phantom, as shown in Fig. 1a, was used to generate analytically projection data, which contain the continuous-to-discrete inconsistency. From the inconsistent data set, images were reconstructed by use of different selections of ϵ . In Figs. 1b, c, and d, we show three images reconstructed by use of the TV-based algorithm with different constraint parameter $\epsilon=8.96$, 11.0, and 13.1. The root-mean-square errors (RMSEs) between the true image and three reconstructed images, as an index of the image quality, have been calculated. The RMSE for these three image sets are 28.9, 31.3, and 33.2, respectively. It can be observed that, the RMSE is increased as ϵ increases. In general, for a larger constraint parameter ϵ , the reconstructed image with a smaller total variation.



Figure 1: The true image (a) and the images reconstructed with different constraint parameter $\epsilon=13.1$ (b), $\epsilon=11.0$ (c), and $\epsilon=8.96$ (d). The display gray scale is [0.8, 1.2].

1.2 Investigation of scanning configurations in tomosynthesis

In conventional tomosynthesis, the X-ray source generally is moved along a curve within a plane, such as a circular trajectory. Because of the limitation of the angular coverage, it is always challenging to obtain the images of high quality from conventional tomosynthesis data. During the last year, we have proposed a new imaging strategy by using non-planar trajectory for increasing data information in tomosynthesis, which may result in the improvement of the reconstructed image quality without increasing the imaging radiation dose [5]. In the investigation of this new imaging approach to tomosynthesis imaging, we have considered a set of non-planar trajectories distributed over a curved surface, and we use the TV-based

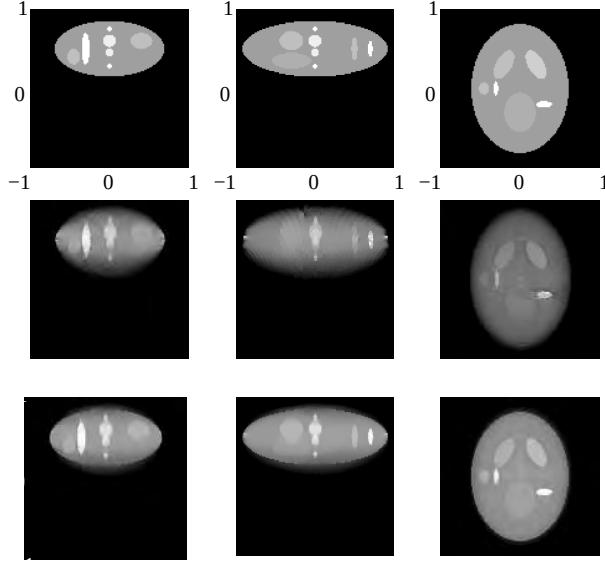


Figure 2: The true image (top row) and the images reconstructed from projection data acquired with the planar trajectory (middle row) and the non-planar trajectory (bottom row). The first to third columns represent the 2D slices at $x = 0$ cm, $y = 0$ cm, and $z = 0.5$ cm, respectively. The display gray scale is $[0, 2]$. The horizontal and vertical axes have a unit of cm.

algorithm to reconstruct images from tomosynthesis data acquired with planar and non-planar trajectories. Below, we summarize the research result on a source trajectory that consists of two orthogonal curve segments on a portion of a spherical surface. In particular, the source to rotation center is 7.0 cm. A flat-panel detector is placed perpendicular to the line connecting the source and the rotation center. The source-to-detector distance is 10.0 cm. A 3D phantom is used to generate cone-beam projection data. We have also generated analytically the data so that the data contain the continuous-to-discrete inconsistency. We first generated projection data from the phantom at 30 views uniformly distributed on the planar circular trajectory described above. From the data, we subsequently reconstructed images by using the TV-based algorithm, and we displayed in the middle row of Fig. 2 the reconstructed images within planes specified by $x = 0$ cm, $y = 0$ cm, and $z = 0.5$ cm.

We then consider a non-planar trajectory that consists of two orthogonal, circular segments. In this configuration, the geometric parameters such as the source-to-rotation-center distance and detector-to-source distance were chosen to be identical to those in the above study for the planar circular trajectory. Using this non-planar trajectory, we generate analytically projection data from the same phantom over total 30 views of which 15 views are uniformly distributed on each of the two orthogonal circular segments. The number of views over one of the two trajectories is only one half of that for the planar trajectory. Therefore, the total imaging radiation doses in the studies involving the planar and non-planar trajectories are the same. From the generated data, we reconstructed images by use of the TV-based algorithm. In the bottom row of Fig. 2, we show the reconstructed images within planes specified by $x = 0$ cm, $y = 0$ cm, and $z = 0.5$ cm, respectively. We also display in Fig. 3 the profiles in the reconstructed images along the axes specified by $x = 0$ cm and $y = 0$ cm, by $y = 0$ cm and $z = 0$ cm, and by $x = 0$ cm and $z = 0$ cm, respectively. Comparison of the results in Figs. 2 and 3 suggests that with the same number of views (or, equivalently, the same amount of imaging dose), data acquired with our proposed non-planar trajectory tomosynthesis may contain more information than that acquired with the conventional tomosynthesis, leading to images with improved quality.

1.3 Investigation of the scatter in tomosynthesis imaging

In realistic tomosynthesis imaging, a number of physical factors can significantly affect image quality, thereby resulting in poor detection of mass and microcalcification in breast. In this project, we have

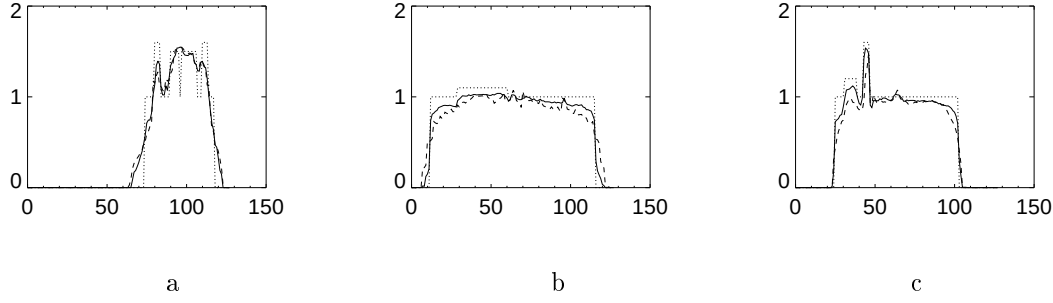


Figure 3: The profiles of the reconstructed images obtained from projection data acquired with the planar trajectory (dashed curve) and the non-planar trajectory (solid curve) along the z -axis at $x = 0$ cm and $y = 0$ cm (a), the x -axis at $y = 0$ cm and $z = 0$ cm (b), and y -axis at $x = 0$ cm and $z = 0$ cm, respectively. The dotted curve indicates the true profiles along these lines.

conducted investigation of the impact of the major physical factors, including data noise, non-isotropic image spatial resolution, scatter, beam-hardening, and detector responses. Based upon our initial studies of last year, we have focused on further investigating the effects of data noise, and non-uniform image resolution and on the effect of scatter on image quality. We summarize briefly our scatter investigation below. The effect of X-ray scatter poses a challenging problem in breast tomosynthesis imaging because the precise functional form of the distribution of the scattered radiations depends on the subject being scanned [6]. Taking advantage of the fact that the scattered X-ray intensity does not display significant high-resolution structures, we used a convolution method in our study of scatter effect. Specifically, we have employed an existing scatter kernel in literature to generate scatter components in tomosynthesis projection data [7]. We have generated and evaluated scatter components for projection angles: 0° , 6° , 12° , 18° , 24° , and 30° , which are typical angles in breast tomosynthesis. Based upon the convolution kernel and scatter components, we determined the scatter kernel for any projection angle by use of interpolation/extrapolation methods. Once we obtain these kernels for any angles, we then generated the scatter components for any projection view by convolving the scatter-less projection data with the scatter kernel. This tool for generating scatter components in breast tomosynthesis allows us to conduct qualitatively the effect of scatter on image reconstruction in the next few months.

KEY RESEARCH ACCOMPLISHMENTS

- We have generated analytically the data containing the continuous-to-discrete inconsistency.
- We have conducted a preliminary investigation of the performance of the TV-based algorithm with different constraint parameter ϵ for the data containing continuous-to-discrete inconsistency.
- We have implemented the modification to the TV-based algorithm to incorporate the non-planar trajectory.
- We have conducted preliminary investigations of the scanning configurations in tomosynthesis breast imaging for improving image quality.
- We have performed a preliminary study on the effect of the non-isotropic spatial resolution.
- We have generated the scatter component for any projection view in breast tomosynthesis breast imaging by convolving the scatter-free projection data with the scatter kernel.

REPORTABLE OUTCOMES

Conference Articles

1. **D. Xia**, J. Bian, E. Sidky, and X. Pan: Image representation with non-isotropic spatial resolution on iterative reconstruction accuracy in breast tomosynthesis, RSNA scientific assembly and annual meeting program, SSC13-01, 2007.
2. **D. Xia**, J. Bian, E. Y. Sidky, C. A. Pelizzari, and X. Pan: Tomosynthesis with Source Positions Distributed over a Surface, Proc. SPIE, Vol. 6913, pp. 69132A, 2008.

CONCLUSIONS

During the period from 15 March 2007 through 14 March 2008, we have investigated and evaluated the performance of the TV-based algorithm for image reconstruction for the tomosynthesis data containing inconsistency. The numerical studies are conducted to investigate the image reconstruction by use of the TV-based algorithm with different constraint parameter ϵ . The relationship between the image quality, in terms of the metrics such as root-mean-square error, and the constraint parameter ϵ has been established. Furthermore, a new imaging strategy by using non-planar trajectory has been proposed and evaluated for increasing data information in tomosynthesis. Our results suggest that with the same number of views (or, equivalently, the same amount of imaging dose), data acquired with the proposed non-planar trajectory tomosynthesis may contain more information than that acquired with the conventional tomosynthesis, leading to images with improved quality. We have begun to investigate the effect of scatter on image quality. A convolution method had been used in our study to estimate the scatter in breast tomosynthesis. Overall, we have achieved the goals for the second year and laid the foundation for the research in the next year. For the third year of this grant our efforts will focus on the evaluation studies of reconstruction algorithms about more physical factors such as non-linear partial volume, beam-hardening, and scatter. Moreover, we will also perform tomosynthesis experiments to collect real data of physical breast phantoms for additional evaluation of the scanning configurations and reconstruction algorithms. Finally, we plan to select real-patient data for testing and assessing the reconstruction algorithm.

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APPENDICES

- Appendix A: **D. Xia**, J. Bian, E. Sidky, and X. Pan: Image representation with non-isotropic spatial resolution on iterative reconstruction accuracy in breast tomosynthesis, RSNA scientific assembly and annual meeting program, SSC13-01, 2007.
- Appendix B: **D. Xia**, Junguo Bian, Emil Y. Sidky, Charles A. Pelizzari, and Xiaochuan Pan: Tomosynthesis with source positions distributed over a surface, Proc. SPIE, Vol. 6913, pp. 69132A, 2008.

Image representation with non-isotropic spatial resolution on iterative reconstruction accuracy in breast tomosynthesis

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Clinical Relevance/Application:

Breast tomosynthesis has received renewed interest because it can provide 3D information about the breast. This work concerns iterative reconstruction of accurate breast tomosynthesis images.

Purpose:

In current breast tomosynthesis, image representation with non-isotropic spatial resolution is used for reducing computational time. This can, however, lead to artifacts in iterative reconstruction of breast tomosynthesis images. In the work, we investigate the effect of non-isotropic image representation on the reconstruction accuracy. Based upon the investigation, we devise schemes for reducing artifacts in iterative reconstruction.

Materials and Method:

In the work, we focus on investigating the effect of non-isotropic image representation on reconstruction accuracy of iterative algorithms. The iterative algorithms under study include the total-variation (TV) based, expectation maximization (EM), and algebraic reconstruction technique (ART) algorithms. Tomosynthesis data are generated at 12 and 20 views over 50 degrees from phantoms, including a breast phantom. We have reconstructed images by using image representations with different degrees of non-isotropic spatial resolution. Specifically, in each image representation, the ratio between the in-plane and longitudinal resolution for an image voxel is selected to be a value less than 1.

Results:

We have reconstructed images by use of TV-based, EM, and ART algorithms for image representations with different ratios of in-plane and longitudinal resolution. Our results demonstrate that non-isotropic image representation can lead to significant artifacts in reconstructed images. The appearance and severity of the artifacts depend not only upon the ratio between the in-plane and longitudinal resolution but also upon the iterative algorithms. The TV-based algorithm seems to be less susceptible to the effect than the EM and ART algorithms. Through the selection of algorithm parameters, the artifacts can be reduced.

Conclusion:

The non-isotropic image representation can significantly affect reconstruction accuracy obtained with iterative algorithms in breast tomosynthesis.

Tomosynthesis with Source Positions Distributed over a Surface

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February 29, 2008

Abstract

In classical tomosynthesis, the X-ray source generally is moved along a curve segment, such as a circular trajectory, within a plane that is perpendicular to the detector plane. Studies suggest that, when the angular coverage and number of projection views are limited, it can be difficult to reconstruct accurate images within planes perpendicular to the detector plane in classical tomosynthesis. In this work, we investigate imaging strategies in tomosynthesis using trajectories that are not confined within a plane perpendicular to the detector plane. We expect that such trajectories can increase data information and thus lead reconstructed images with improved quality. Numerical studies were conducted for evaluating the image-reconstruction quality in classical tomosynthesis and tomosynthesis with trajectories that are not confined within a plane perpendicular to the detector plane. The results of the studies indicate that, with the same number of views, (or, equivalently, the same amount of imaging radiation), data acquired in tomosynthesis with the trajectories that are not confined within a plane perpendicular to the detector plane generally contain more information than that acquired with classical tomosynthesis and can thus yield images with improved quality.

1 Introduction

In the past decade or so, there have been renewed interests in the development of tomosynthesis for applications to breast imaging, image-guided radiation therapy, and security scans [1, 2]. In these studies, the X-ray source often is moved along a curve segment within a plane that is perpendicular to the detector plane. For convenience, we refer to such a source trajectory as a planar trajectory. In some practical applications of tomosynthesis, however, the source trajectory need not be restricted to be within a planar trajectory, and it can be a trajectory in 3D space. For example, the X-ray source may move over a surface such as a portion of the sphere in some applications. In these cases, we refer to the trajectories as non-planar trajectories. We hypothesize that tomosynthesis with certain non-planar trajectories can yield images with improved quality over that obtained with a planar trajectory. In this work, we conduct a preliminary investigation of image reconstruction in classical tomosynthesis that uses a planar trajectory and tomosynthesis that uses a non-planar trajectory. We will apply the TV-minimization iterative algorithm for image reconstruction from data acquired in the two tomosynthesis configurations [3, 4].

2 Scanning configurations for tomosynthesis

In classical tomosynthesis, the x-ray source is moved along a curve segment. When the curve segment is a portion of a circular trajectory, it can be expressed mathematically as

$$\vec{r}_0(\lambda) = (R \sin \lambda, 0, R \cos \lambda) \quad \lambda \in [\lambda_s, \lambda_e], \quad (1)$$

where λ denotes the rotation angle, R is the distance from the source point to the rotation center, and parameters λ_s and λ_e denote the starting and ending angles of the rotation. For each rotation angle λ , a 2D detector is used to measure the projection data, which is the path integral of the x-ray attenuation

coefficient along the rays connecting the source spot and an individual detector bin. In terms of discrete detector array and image array, the data model can be written as the weighted sum over the pixels traversed by the source-bin ray, i.e.,

$$\vec{g} = M\vec{f}, \quad (2)$$

where $\vec{f}$ and $\vec{g}$ are two finite vectors, representing the image function and projection data. The dimensions of $\vec{f}$ and $\vec{g}$ are N_{image} and N_{data} , which denote the elements of discrete image and data arrays. The system matrix M thus composes N_{data} row vectors $\vec{M}_i$ of dimension of N_{image} , yielding $g_i = \vec{M}_i \cdot \vec{f}$. Each element M_{ij} of the system matrix is the length of the i th ray traversing the j th pixel. The process of image reconstruction is to obtain an image represented by the finite vector $\vec{f}$ from knowledge of the data vector $\vec{g}$ and the system matrix M .

In classical tomosynthesis for breast imaging, projection data are measured at about 20 projection views uniformly distributed over an angular range of about 30° . One may improve the image quality of classical tomosynthesis by increasing the number of projections and/or the scanning angular range. However, this approach results in increased imaging radiation dose to the subject. On the other hand, it may be possible to design innovative scanning configurations for acquiring more information than that collected with a planar trajectory in Fig. 1a in classical tomosynthesis, yet without increasing the imaging radiation dose. In this work, we investigate a non-planar imaging configurations in tomosynthesis for acquiring increased data information and thus for achieving improved image quality. In contrast to the planar trajectory in classical tomosynthesis, we study in this work a non-planar trajectory that is on a curved surface. In particular, we consider a source trajectory that consists of two orthogonal curve segments on a portion of a spherical surface, as shown in Fig. 1b. The two curve segments of the non-planar trajectory are expressed as

$$\vec{r}_0(\lambda) = (R \sin \lambda, 0, R \cos \lambda) \quad \lambda \in [\lambda_s, \lambda_1], \quad (3)$$

$$\vec{r}_0(\lambda) = (0, R \sin(\lambda), R \cos(\lambda)) \quad \lambda \in [\lambda_2, \lambda_e]. \quad (4)$$

It can be observed that the two circular segments are chosen to be within x - z and y - z planes. Both of them are on a spherical surface of radius R . Clearly, they are not within a single plane. In this work, we will investigate and compare images reconstructed by use of the TV-minimization algorithm from data acquired with the planar trajectory in classical tomosynthesis and from data obtained with the non-planar trajectory.

3 Reconstruction algorithm

We briefly review the TV-minimization algorithm [3] that is used to reconstruct images from tomosynthesis data in this work. In many imaging applications, it is not uncommon that images to be reconstructed are relatively constant over extended volumes, and that significant, rapid variation in the image may occur only at boundaries of internal structures. In these situations, the image formed by taking the magnitude of its gradient could be approximately sparse. Therefore, the reconstruction strategy considered in the TV-minimization algorithm is to incorporate the assumption of gradient image sparseness on the image function $\vec{f}$ to arrive at a solution from knowledge of the data $\vec{g}$. Based upon this strategy, the TV-minimization algorithm seeks to find the solution for the optimization problem below:

$$\vec{f}^* = \text{argmin} \|\vec{f}\|_{TV}, \quad (5)$$

with two constraints,

$$\|M\vec{f} - \vec{g}\| \leq \epsilon \quad \text{and} \quad f_i \geq 0,$$

where $\vec{f}^*$ is the reconstructed image. The inequality used in the first constraint accounts for data inconsistency, such as noise, continuous-to-discrete inconsistency. The parameter ϵ can be selected for controlling the impact level of potential data inconsistency on the image reconstruction. In our investigation of 3D tomosynthesis reconstruction, the TV of a discrete image is defined as

$$\|\vec{f}\|_{TV} = \sum_{s,t,r} |\vec{\nabla} f_{s,t,r}| = \sum_{s,t,r} \sqrt{(f_{s,t,r} - f_{s-1,t,r})^2 + (f_{s,t,r} - f_{s,t-1,r})^2 + (f_{s,t,r} - f_{s,t,r-1})^2}, \quad (6)$$

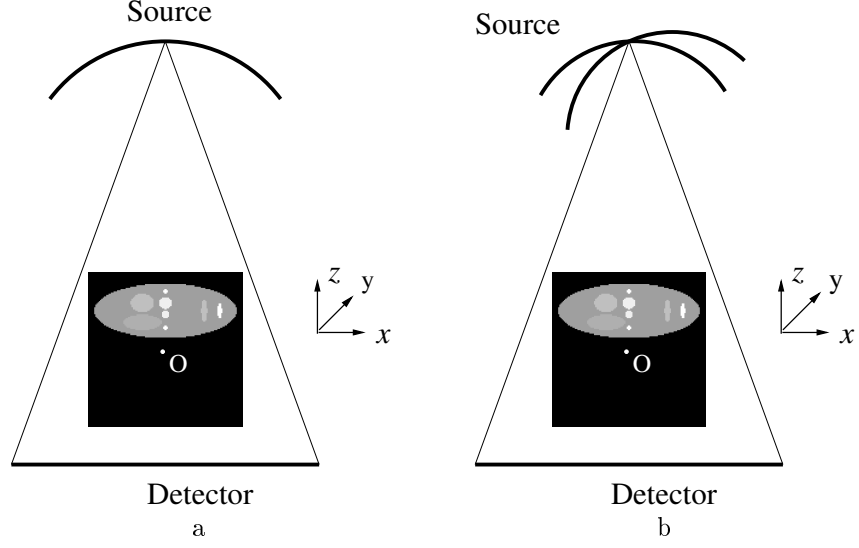


Figure 1: (a) Scanning configuration with a planar trajectory within x - z plane in classical tomosynthesis. (b) Scanning configuration with a non-planar trajectory that consists of two orthogonal, circular segments within x - z and y - z planes, respectively (right).

where s , t , and r indicate the pixel indices within the 3D image.

The implementation of the TV-minimization algorithm includes two major steps: gradient descent method and projection on convex sets (POCS) (see e.g. Sec. 15.4.5 of Ref. [5]). The gradient descent method is used for minimizing the image total variation, whereas the POCS is used for enforcing the constraints imposed by the known projection data. The reason the POCS is used here is that, even in the case of sparse sampling, the size of the projection data sets can be large, and POCS can efficiently handle large data sets.

4 Results

We have conducted numerical studies to investigate image reconstructions by using the TV-minimization algorithm from tomosynthesis data acquired with planar and non-planar trajectories shown in Fig. 1. We use $\vec{r}_0(\lambda)$ to denote a source trajectory. In our study, we first consider classical tomosynthesis in which the source trajectory is a segment of the planar circular trajectory, as shown in Fig. 1a. In the study, we have chosen $R = 7.0$ cm, and $\lambda \in [-\pi/6, \pi/6]$. A flat-panel detector is placed perpendicular to the line connecting the source and the rotation center. The source-to-detector distance is 10.0 cm. A 3D phantom is used to generate cone-beam projection data. It should be pointed out that we have generated analytically the data so that the data contain the so-called continuous-to-discrete inconsistency to reflect realistic imaging conditions in practical tomosynthesis. Such inconsistency may have a significant impact on reconstruction accuracy. In top row of Fig. 2, we display the phantom images within planes specified by $x = 0$ cm, $y = 0$ cm, and $z = 0.5$ cm, respectively. We first generated projection data from the phantom at 30 views uniformly distributed on the planar circular trajectory described above. From the data, we subsequently reconstructed images by using the TV-minimization algorithm, and we displayed in the middle row of Fig. 2 the reconstructed images within planes specified by $x = 0$ cm, $y = 0$ cm, and $z = 0.5$ cm.

We also consider a non-planar trajectory that consists of two orthogonal, circular segments, as shown in Fig. 1b. In this study, geometric parameters such as R and detector-to-source distance were chosen to be identical to those in the above study for the planar circular trajectory. However, the angular ranges of the two orthogonal circular segments are specified by $\lambda \in [-\pi/6, \pi/6]$ and $\lambda \in [\pi/6, \pi/2]$, respectively. Using this non-planar trajectory, we generate analytically projection data from the same phantom over total 30 views of which 15 views are uniformly distributed on each of the two orthogonal circular segments.

The number of views over one of the two trajectories is only one half of that for the planar trajectory. Therefore, the total imaging radiation doses in the studies involving the planar and non-planar trajectories are the same. From the generated data, we reconstructed images by use of the TV-minimization algorithm. In the bottom row of Fig. 2, we show the reconstructed images within planes specified by $x = 0$ cm, $y = 0$ cm, and $z = 0.5$ cm, respectively. We also display in Fig. 3 the profiles in the reconstructed images along the axes specified by $x = 0$ cm and $y = 0$ cm, by $y = 0$ cm and $z = 0$ cm, and by $x = 0$ cm and $z = 0$ cm, respectively. Comparison of the results in Figs. 2 and 3 suggests that tomosynthesis with a non-planar trajectory may yield more data information, and thus images with higher quality, than classical tomosynthesis with a planar trajectory.

5 Conclusion

In the work, we have investigated non-planar trajectories in tomosynthesis for yielding more data information than classical tomosynthesis with a planar trajectory. Our preliminary study indicates that with the same number of projection views (or, equivalently, the same dose level,) the new imaging configuration may lead to images with improved quality over that obtained with classical tomosynthesis. The proposed imaging strategy and TV-minimization reconstruction algorithm may find applications in IGRT, security scan, industrial imaging, and sample/specimen evaluation.

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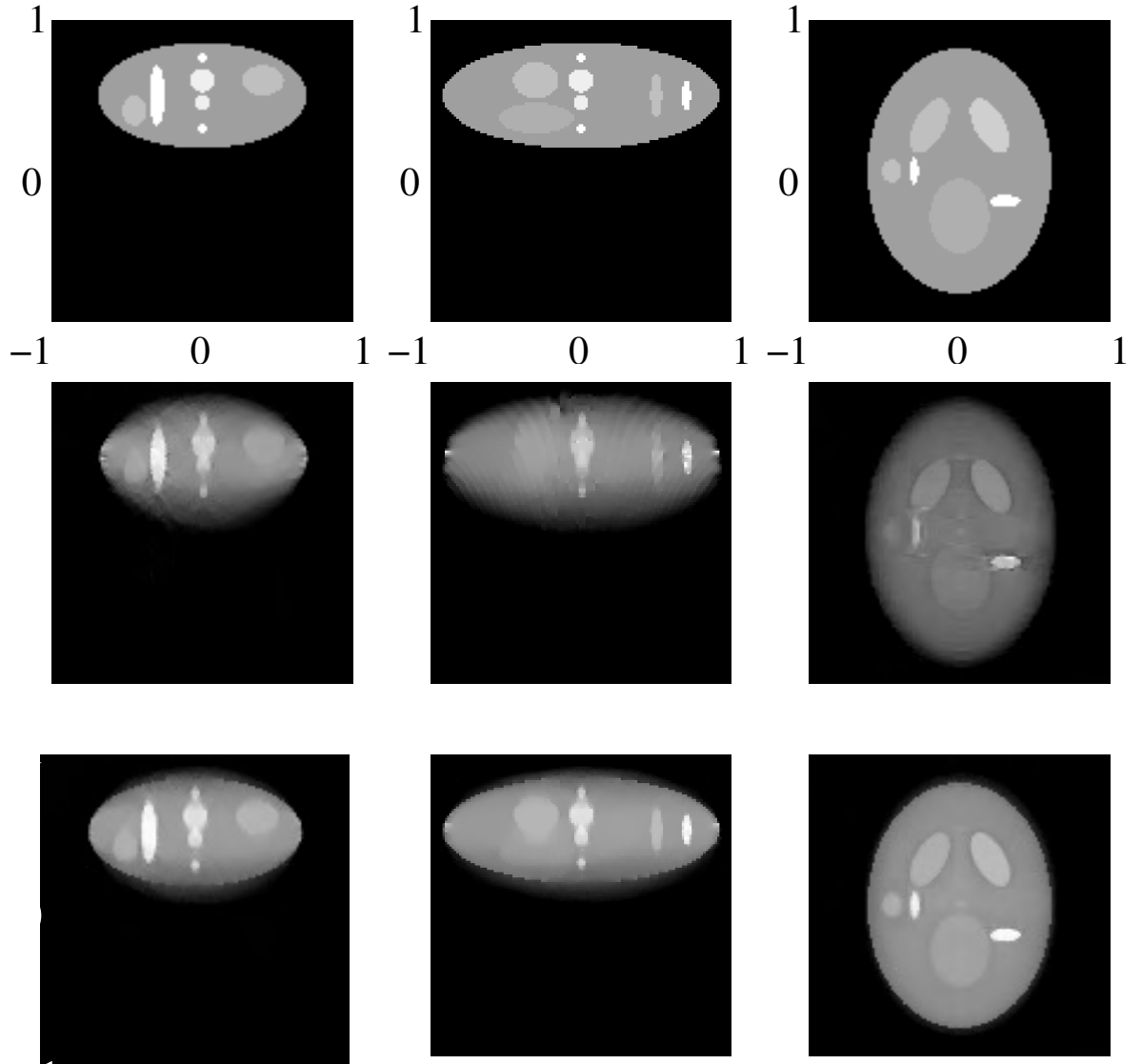
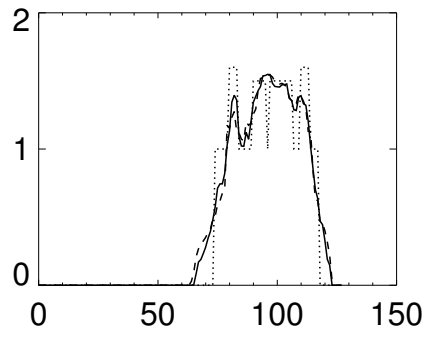
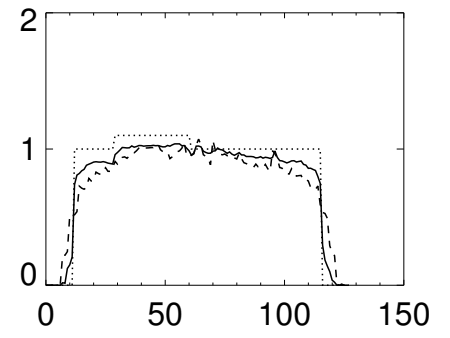


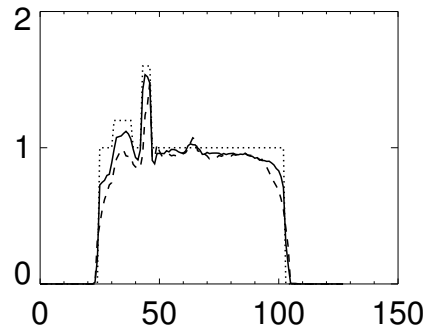
Figure 2: True image (top row) and images reconstructed from 30-view projection data acquired with the planar trajectory (middle row) and the non-planar trajectory (bottom row). The first, second, and third columns represent the images within 2D slices specified by $x = 0$ cm, $y = 0$ cm, and $z = 0.5$ cm, respectively. The display gray scale is $[0, 2]$. The horizontal and vertical axes have a unit of cm.



a



b



c

Figure 3: Profiles of the images reconstructed from 30-view projection data acquired with the planar trajectory (dashed curve) and the non-planar trajectory (solid curve) along (a) the z -axis, (b) the x -axis, and (c) y -axis, respectively. The dotted curve indicates the true profiles along these lines.