Feasibility Studies on Low-dose Cone-beam 3-D Mammography

Zhengrong Liang, Hongbing Lu, Junhai Wen, Tianfang Li, Wei Zhao, Jiang Hsieh, Ge Wang and Roxanne Palermo

***Abstract*—Breast cancer is the most frequent cause of deaths for women in USA. Currently available digital mammography provides excellent spatial resolution and tissue contrast with a reasonable soft X-ray radiation dosage. With further technology development, the resolution and contrast would be further improved toward early detection of the cancer. A main limitation of the conventional digital mammography is the overlap of tissues along the projection of X-rays onto the detector, in addition to the complication for intervention because of the structural distortion associated with the breast compression. Three-dimensional (3D) mammography has been investigated in past years, aiming to remove the overlap limitation. A significant problem for 3D mammography is its increased radiation, as compared to the conventional mammography. This work aims to reduce the radiation, while achieving high quality 3D mammography, by investigating (1) an optimal system configuration for as complete as possible data sampling with least projections and (2) an effective noise reduction on the acquired data with as less as possible X-rays. An optimal data sampling orbit was suggested after investigating several candidates with cone-beam geometry. An effective noise reduction framework was established, which could achieve more than ten times radiation reduction while retaining the same image quality. Further investigation and validation are under progress.**

***Index Terms*—Low-dose 3D mammography; Cone-beam image reconstruction; Computer aided detection.**

I. Introduction

Breast cancer is the most frequent cause of deaths for women in USA. Yet the diagnosis in an early stage is not efficient by currently available means. Although advanced digital mammography with excellent spatial resolution and tissue contrast is currently available as a screening modality with very sophisticated computer aided detection (CAD) means to help the Radiologists to identify any malignant abnormality, the accuracy or specificity is still relatively low. Frequently, biopsy is needed. Most of the biopsies insert a marker at the target site to facilitate the follow-up management because of the tissue distortion by the breast compression. Without three-dimensional (3D) image guidance, the biopsy may take a sample, which does not belong to the target, or the inserted marker may shift inside the compressed breast in the follow-up resection. Therefore, the currently available means for screening of early breast cancer generates more than half undetermined cases, resulting in more than two thirds of unnecessary biopsies and a significant amount of normal tissues being resected – a costly cosmetic operation (American Cancer Society, www.cancer.org).

We contend that the information embedded in a 2D projection image of a compressed breast is not significantly more than that of a projection image of an uncompressed breast, because the projection overlap of breast tissues along the X-ray paths remains, although it is in a less degree. Therefore, 3D mammography can provide both a fully 3D image of the breast and any projection image of the 3D object. It is helped that the 3D information will improve the diagnosis and surgical intervention.

Removal of the tissue-overlap limitation of the conventional 2D digital mammography for a fully 3D mammography has been attempted by many researchers in the past years across the world. Technically, reconstruction of a 3D high resolution, high contrast image of the breast from projections, which are adequately sampled around the object, could be achieved by currently available computer tomography (CT) technologies. But the increased radiation dosage by multiple projections limits its clinical applications as a screening modality. Alternatives utilizing non-ionization modalities, such as magnetic resonance imaging (MRI), PET (positron emission tomography), Ultrasound and optical imaging, have been investigated in the past decades with some success, but each has its own limitations, see the references of [2] for more detailed information.

Reduction of the soft X-ray radiation for 3D mammography has been a research focus in the past years for many reasons. One may be due to the high spatial and temporal resolution of X-ray imaging, and the other can be the instrumental cost. Figure 1 below shows a typical research prototype, perhaps the most feasible one, of many instruments, where a high sensitive flat-panel detector is used to minimize the needed X-rays, therefore, resulting in a radiation reduction. We have been interested in software approaches to achieve the same goal of minimizing the radiation [3-5]. In this paper, we

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present some preliminary studies on low-dose 3D mammography, based on the prototype system of Figure 1.

II. Method and Results

Our software approaches aim to find (1) a minimal electrical current across the X-ray tube (i.e., mA), which provides sufficient information so that our noise reduction strategy can extract the information reliably; and (2) a minimal number of projections with sufficient sampling of the object, based on the prototype of Figure 1. The first aim of noise reduction is described below.

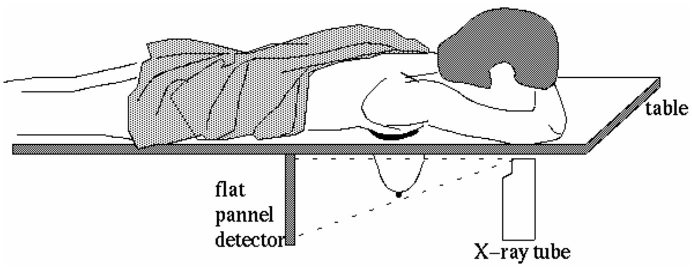

Figure 1: A prototype of 3D mammography with high spatial resolution, high detection efficiency flat-panel detector.

A. Noise Reduction Strategy

Our strategy for noise reduction in low-dose CT consists of two parts. The first part is to establish the ground true of the variance-mean relation (VMR) and the probability density function (PDF) of the projection measurements from anthropomorphic phantoms. This part was performed by repeatedly scanning the phantom several hundred times. The average of these scans provides good estimates of the means respectively, which cover a wide range from 10 to over a thousand. From these estimated means and the repeatedly scans, the variance can be computed for each mean, respectively, resulting in a VMR curve. Similarly we grouped those samples with the same mean and computed the histogram from those samples for that mean. An analytical form of PDF can be fitted from the computed histograms. This experimental study basically agrees with the theoretical prediction on PDF in [1] and VMR in [6].

Given the established ground true of VMR and PDF, the second part of our strategy is to design a scale transform to minimize any non-stationary behavior of the measurements, followed by the Karhunen-Loeve (K-L) transform. In the K-L domain, the variance remains, but the signal (which is proportional to the eigenvalue) is arranged in an ordered manner corresponding to the associated principal components. In other words, we have obtained the signal-to-noise ratio (SNR) for each component in the K-L domain. Then a weighted (by the given VMR) cost function (from the PDF) is minimized by analytical algorithms for the solution of the estimated "noise-free" projection data. In our case, the PDF is a Gaussian, therefore, the cost function becomes the penalized weighted minimum least-square criterion for each K-L component in the sinogram space. We employed singular decomposition technique as our analytical algorithm to invert the covariance matrices associated with the K-L and/or scale transforms. Reconstruction of the estimated "noise-free" projections for the source image is performed by the well-established filtered backprojection (FBP) algorithm. An example is given by Figure 2 below [3-5].

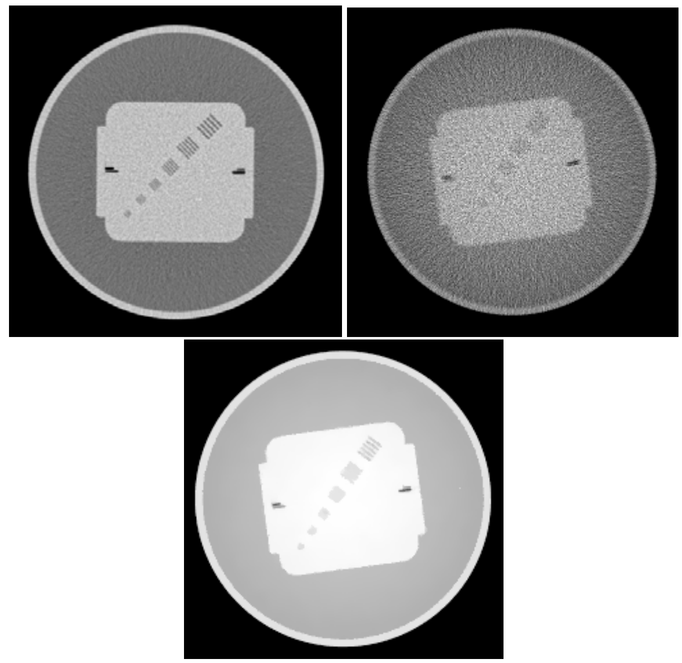

Figure 2: The GE quality assurance phantom was repeated scanned 19 times by a GE 4-detector array spiral CT. The top left shows a slice image of FBP reconstruction from the summation of the 19 scans (Ramp filter with the Shapp-Logan low-pass window at Nyquist frequency cutoff). On the top right is the FBP reconstruction from a single scan (the same filtering was applied). The bottom shows the FBP reconstruction after our noise reduction on the projection data (Ramp filter at the Nyquist frequency cutoff was used for the FBP algorithm). Our reconstruction from a single scan improves the image quality significantly, as compared to the currently available CT technology (top right), and approaches closely to the result from 19 repeated scans (top left). If the radiation dose is linearly proportional to the number of scans, then our low-dose CT software module can achieve more than ten times radiation reduction.

The satisfactory noise reduction lies down a foundation to achieve low-dose CT for massive screening of the vital organs, such as the heart, lungs, and colon, by currently available whole-body spiral CT hardware configuration without any additional cost, except for a software program which runs a few minutes on a current PC workstation. For screening the breast cancer, the current CT technology may not be the optimal configuration. The research prototype of Figure 1 could be an optimal configuration for 3D mammography. Our second aim of finding a minimal number of projections with sufficient sampling of the object is described below, based on the prototype of Figure 1. The software remains the same.

B. Cone-beam Sampling Strategy

By the prototype of Figure 1, a circular orbit of the half cone-beam geometry can provide very good reconstruction if the X-ray source is far away from the object so that the oblique rays along/toward the z-axis (vertical direction) could have a minimal effect on the reconstruction even if they do not satisfy the sufficiency condition [7]. For a relative short distance between the source and the object for an improved spatial resolution, the circular orbit may not be an optimal choice. Ning, *et al*. [8, 9] proposed a circular plus arc orbit to satisfy the sufficiency condition. We contend that a full circular orbit may not be optimal, because of the redundancy of the sampling near the chest base, where the half cone X-rays have similar effects as fan-beam geometry. In this work, we investigated three alternative orbits, attempting to save some samples in the circular orbit for axial sampling, while satisfying the sufficiency condition.

1). *Two near half-circular orbits:* In this sampling, one near half-circular (180^o plus a fan-angle) orbit at the chest base and the other near half-circular (180^o plus fan-angle) orbit at the breast tip or nipple (with opposite oblique half cone rays toward the chest base) were applied. Both orbits together cover a full circular orbit plus two fan-angles.

2). *Two near half-spiral orbits:* In this sampling, one near half-spiral orbit of 180^o plus a fan-angle was applied starting from the chest base. The other near alf-spiral orbit of 180^o plus fan-angle started at the breast tip (with opposite oblique half cone rays toward the chest base) back to the chest base. Both orbits together cover a full circular orbit plus two fan-angles. The orbits at the object middle provide full cone rays with truncation (preventing X-rays from going into the chest base).

3). *A near half-circular plus a near half spiral orbits:* In this sampling, one near half-circular (180^o plus a fan-angle) orbit at the chest base was applied and then a near half-spiral orbit at the breast tip (with opposite oblique half cone rays toward the chest base) was applied. The spiral orbit provides full cone rays with truncation (preventing X-rays from going into the chest base).

The reconstruction was performed by the generalized Feldkamp cone-beam reconstruction algorithm developed by Wang, *et al*. [10, 11]. Some preliminary results are presented by Figures 3 and 4 below.

III. Discussion and Conclusion

Noise reduction for limited photon detection was investigated to achieve as low as possible the mA parameter for low-dose CT modality. The strategy is based on as much as possible the ground true.

Three alternatives to the full-circular orbit of a half cone-beam geometry was studied for 3D mammography with flat panel detector configuration. All of them provide an adequate sampling through the whole object for a shorter distance between the X-ray source and the object. The two near half-circular orbits have the advantage of easy implementation and could be the choice for practical reasons. More extensive investigation on other alternative orbits is currently under progress.

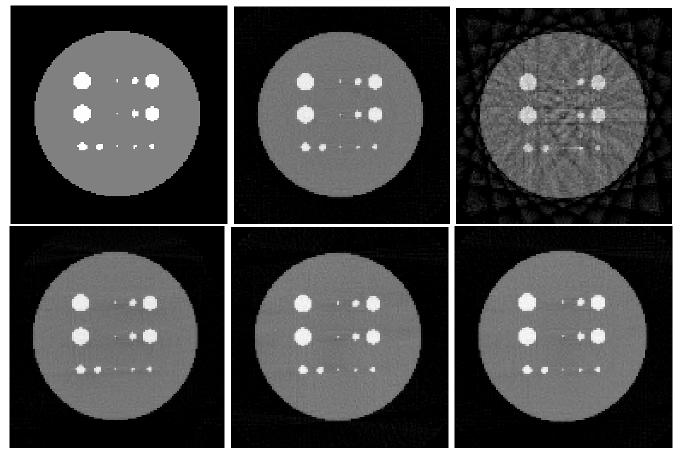

Figure 3: On the top left shows the transverse slice of the simulated phantom. The top middle shows the reconstructed slice image from noise-free cone-beam projection data of circular orbit. The top right shows the reconstruction from noisy data after our noise reduction, where the very noisy data is at the level around 100 counts per detector bin. The bottom left shows the noise-free reconstruction from two near half-circular orbits. The bottom middle shows the noise-free reconstruction of two near half-spiral orbit. On the bottom right shows the near half-circular plus near half spiral orbit. All three non-full circular orbits provide adequate sampling for the whole object and improve the reconstruction near the breast tip when the X-ray source is close to the object for enhanced spatial resolution. The two near half-circular orbits have the advantage of easy implementation and could be the choice for practical reasons. More extensive investigation on the sampling strategy is being pursued. (The slightly low density near the chest base can be compensated by adequate average of the redundant rays. This algorithm development is currently under progress.)

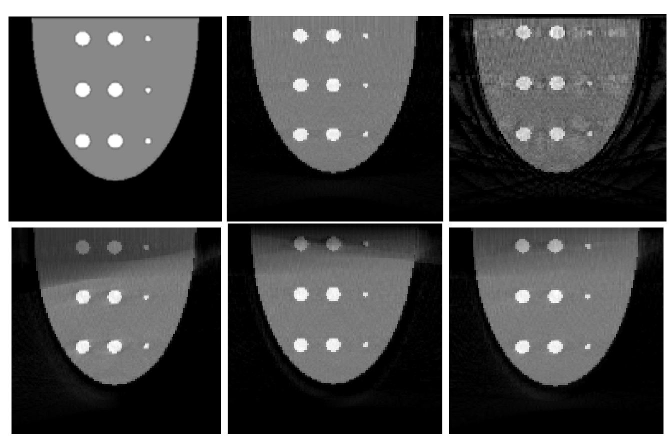

Figure 4: They are a sagittal slice of the simulated phantom and the corresponding reconstruction images of Figure 3.

IV. ACKNOWLEDGMENT

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REFERENCES

[1] H. Barrett and W. Swindell, *Radiological Imaging*, Academic Press, New Yrok, 1969.

[2] J. Boone, T. Nelson, K. Lindfors, and J. Seibert, "Dedicated breast CT: Radiation dose and image quality evaluation", *Radiology*, vol. 221, pp. 657-667, 2001.

[3] H. Lu, I-T. Hsiao, X. Li, and Z. Liang, "Noise properties of low-dose CT projections and noise treatment by scale transformations", *Conference Record of IEEE NSS and MIC*, in CD-ROM, 2001.

[4] H. Lu, X. Li, I-T. Hsiao, and Z. Liang, "Analytical treatment of noise for low-dose CT projection data by penalized weighted least-square smoothing in the K-L domain", *SPIE Medical Imaging*, vol. 4682, pp. 146-152, 2002.

[5] H. Lu, X. Li, L. Li, D. Chen, Y. Xing, M. Wax, and Z. Liang, "Adaptive noise reduction toward low-dose computed tomography, *SPIE Medical Imaging*, to appear, 2003.

[6] K. Sauer and C. Bouman, "A local update strategy for iterative reconstruction from projections", IEEE Trans Signal Processing, vol. 41, pp. 534-548, 1993.

[7] B. Smith, "Cone-beam tomography: recent advances and a tutorial review", *Optical Engineering*, vol. 29, pp. 524-534, 1990.

[8] X. Wang and R. Ning, "A cone-beam reconstruction algorithm for circle-plus-arc data-acquisition geometry cone beam reconstruction", *IEEE Trans Med Imaging*, vol. 18, pp. 815-824, 1999.

[9] R. Ning, B. Chen, R. Yu, and *et al*., "Flat panel detector-based cone-beam volume CT angiography imaging: system evaluation", *IEEE Trans Med Imaging*, vol. 19, pp. 949-963, 2000.

[10] G. Wang, S. Zhao, and P-C. Cheng, "Exact and approximate cone-beam X-ray microtomography (Chap. 1)", In *Focus on multidimensional microscopy (I)*. PC Cheng, PP Huang, JL Wu, G Wang, HG Kim, eds, Singapore: World Scientific, pp.233-261, 1999.

[11] G. Wang, C. Crawford, and W. Kalender, "Multi-row detector and cone-beam spiral/helical CT", *IEEE Trans Med Imaging*, vol. 19, pp. 817-821, 2000.