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Digital tomosynthesis parallel imaging computational analysis with Shift and Add and Back Projection reconstruction algorithms

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Abstract

Digital tomosynthesis is a novel technology that has been developed for various clinical applications. Parallel imaging configuration is utilised in a few tomosynthesis imaging areas such as digital chest tomosynthesis. Recently, parallel imaging configuration for breast tomosynthesis began to appear too. In this paper, we present the investigation on computational analysis of impulse response characterisation as the start point of our important research efforts to optimise the parallel imaging configurations. Results suggest that impulse response computational analysis is an effective method to compare and optimise imaging configurations.

Keywords

mammography; tomosynthesis; impulse response; SAA; shift and add; BP; back projection; image reconstruction

1 Introduction

Digital tomosynthesis is a novel three-dimensional imaging technology that utilizes limited number of X-ray projection images to improve the diagnosis and detection of lesions (Dobbins and Godfrey, 2003). Various research projects have been conducted by research institutions and manufacturers for quite a few different clinical applications, including chest tomosynthesis imaging, joints imaging, imaging guided therapy, dental imaging, etc. (Dobbins and Godfrey, 2003), and most recently, breast imaging application (Wu et al., 2003).

In the past, owing to limited technology in the areas of computer processing and digital detector, digital tomosynthesis was unable to be developed quickly in its early stages. With the rapid development of modern scientific technologies, the technique of tomosynthesis becomes to be more mature recently (Dobbins and Godfrey, 2003). Modern technologies such as the development of Graphics Processing Unit (GPU) allow reduced computer processing time for certain breast tomosynthesis imaging reconstruction algorithms. The appearance of new digital detectors permits faster projection image readings.

Among various tomosynthesis applications, chest tomosynthesis and breast tomosynthesis are two major fields that have caught a lot of attentions from research communities. In chest imaging fields, lung cancer is a serious problem among all cancer deaths. It has been demonstrated that the digital chest tomosynthesis imaging can improve the lung nodule detection, compared with the traditional chest radiography technique (Godfrey et al., 2006).

In breast imaging fields, breast cancer is a common and major concern among women. In the USA, about 12% female will develop breast cancer during their lifetime, and the mortality rate is around 3%. From the estimated report of American Cancer Society, there were 40,610 women who died from breast cancer in 2009 (Baldwin, 2009). Breast cancer is not restricted to only women; it can also be found in men. The breast cancer risk ratio of gender is about 100 : 1 for female vs. male. Some factors affecting one's cancer risk may include age and the birth country of the individual. People have a higher risk of breast cancer when they get older. Persons who are born in North America or Northern Europe have a higher risk of developing breast cancer than other countries (Ganschow et al., 2004). Currently, the most significant technology in detecting the early stages of breast cancer is mammography. Patients who were found to have breast cancer in its early stages tend to live longer than others who were discovered later. However, based on the advanced technology in recent mammographic imaging, 10–30% of breast cancers are still missed (Chen et al., 2007). Furthermore, some cancers are only detected in their mid- or advanced stages. The traditional two-dimensional mammography has limitations that include recall rates and false negative rates, which cause unnecessary anxiety and higher medical costs. In addition, with the traditional mammography imaging technology, a three-dimensional breast object is projected onto the two-dimensional detector. Overlaps in anatomical structures will occur (Chen et al., 2007).

Compared with traditional mammography, digital breast tomosynthesis imaging technology can reconstruct three-dimensional information of objects with high-detailed resolution based on the finite number of projection images. Breast tomosynthesis re-utilises the traditional single-view technique in the two-dimensional mammography. The total radiation exposure level of a tomosynthesis imaging sequence for all projection images from different angles equates or slightly surpasses that of the traditional mammography (Wu et al., 2004). The novel breast tomosynthesis imaging technology has been demonstrated as promising to provide greater sensitivity and specificity of diagnosis (Zhang et al., 2006). It would serve as a valuable alternative to mammography in the near future.

In tomosynthesis image reconstruction fields, different reconstruction algorithms have been developed to provide three-dimensional information of the object. Traditional shift and add (SAA) method is a fundamental reconstruction algorithm, which has been modified by many research groups for tomosynthesis imaging reconstruction applications. For example, Niklason et al. (1997) applied this algorithm to mammography to line up each projection image after stretching it along the direction of X-ray tube's motion and shifting it by an appropriate amount. Suryanarayanan et al. added Tuned-Aperture Computed tomography (TACT) reconstruction method that was developed by Webber (Suryanarayanan et al., 1999, 2000, 2001) to the traditional SAA for tomosynthesis applications. The SAA algorithm also serves as a solid foundation for further deblurring algorithms in breast tomosynthesis fields (Chen et al., 2004). Back Projection (BP) is another mathematical reconstruction method to line up the in-plane structures. A point-by-point calculation on each reconstruction plane is performed for the BP reconstruction (Chen et al., 2007).

Matrix Inversion Tomosynthesis (MITS) (Dobbins and Godfrey, 2003) is a tomosynthesis reconstruction algorithm that was originally investigated by Dobbins et al. It utilises linear algebra to reduce the blur in each reconstruction plane. Filter Back Projection (FBP) reconstruction is used very widely in tomographic imaging fields. Gunter Lautitsch and Haerer (1998) described a filtering process to deal with projection data in frequency domain and evaluated FBP algorithm associated with adjusted filters in human teeth data. Three filters including ramp filter, spectrum filter and profile filter were designed separately to enhance the high-frequency component, improve the signal-to-noise ratio and optimise the depth resolution (Lauritsch and Haerer, 1998). Algebraic Reconstruction Technique (ART) evaluated by Zhang et al. (2006) is an iterative approach to update the X-ray attenuation coefficient model. Maximum Likelihood Expectation Maximisation (MLEM) as an effective reconstruction algorithm shows high potential in removing artefacts, improving the signal-to-noise ratio and enhancing image contrast (Wu et al., 2003, 2004). Because of its relatively complicate expression, the computation itself is time-consuming compared with other tomosynthesis image reconstruction algorithm families.

Various researches on digital tomosynthesis imaging prototype systems and image reconstruction algorithms have also been conducted by research institutions and manufacturers. Digital chest tomosynthesis is commercially available in the market now, mainly utilising a parallel imaging configuration. For breast tomosynthesis imaging, most of the current breast tomosynthesis prototype imaging systems are built upon the digital mammography system with related automatic mechanical and electrical upgrades (Wu et al., 2003; Zhang et al., 2006; Chen et al., 2007). The X-ray tube typically rotates along an arc above the breast object. Recently, breast tomosynthesis parallel imaging prototype system was also developed by our collaborators Zhou et al. (Yang et al., 2008; Lalush et al., 2006). This multi-beam X-ray imaging system uses multiple beam sources that are aligned along a line parallel to the detector surface (Yang et al., 2008). Compared with other commercial tomosynthesis systems, this structure design not only reduces the motion blur associated with the movement of X-ray tube, but also speeds up the total scan process to be 11.2 seconds for a typical 25 views (Chen et al., 2009). This unique design and fast speed acquisition will help to relieve patient's discomfort.

Investigations on image reconstruction and imaging configuration are essential to design tomosynthesis prototype systems, including the parallel imaging devices. In this paper, we instigated two commonly used digital tomosynthesis reconstruction algorithms of SAA and BP as representatives to evaluate parallel imaging configurations, based on impulse response computational analysis. This methodology can also be applied to other imaging configurations such as partial isocentric motion and circular motion. Impulse response is an

effective method to evaluate image quality and signal resolution property of different imaging parameters and image reconstruction algorithms (Balla et al., 2010).

2 Methods

2.1 Computer wire simulation

Wire simulation is used widely in computed tomography and other biomedical imaging fields to evaluate image quality and image reconstruction algorithms. In chest tomosynthesis fields, Godfrey and Dobbins used this method to evaluate the three-dimensional performance of a MITS reconstruction algorithm (Godfrey et al., 2006). In this paper, a computer wire simulation (Balla et al., 2010) was performed to investigate the three-dimensional reconstruction and imaging configuration for the parallel imaging tomosynthesis applications.

Figure 1 shows the diagram of our computer wire simulation. Tomosynthesis sequences of projection images of a thin wire running horizontally through the image space, whose depth varies from $Z = 10$ mm to $Z = 40$ mm from left to right of the three-dimensional space, were computer simulated. z -axis represents the distance from the detector. The wire is placed on the detector with an angle of 45° (Balla et al., 2010). The X-ray sources were simulated as either aligned or moved along a line that is parallel to the detector plane. Parallel imaging configurations of two imaging parameters were investigated including number of projection images (N) and total view angle (VA).

An example of chest tomosynthesis application was illustrated here, with the published imaging parameter approximation of Source to Image Distance (SID) to be 185 cm. The detector area was simulated to be 1024×1024 pixels with a pixel size of 0.4 mm. To evaluate the effects of variation in VA and N , data set of tomosynthesis sequences of the thin wire with two imaging configuration combinations of different numbers of projection images (N) and VA were simulated: (1) $N = 11$, $VA = 50^\circ$; (2) $N = 63$, $VA = 50^\circ$. Simulated tomosynthesis acquisition allowed the generation of the noise-free projection images (Chen et al., 2007; Balla et al., 2010).

Further study is undergoing to analyse and optimise digital tomosynthesis parallel imaging configurations for breast imaging application.

2.2 Tomosynthesis image reconstruction algorithms

SAA is a fundamental image reconstruction algorithm in digital tomosynthesis fields. When the X-ray tube moves, object structures at different positions in the three-dimensional space will be projected onto the detector differently, depending on the relative heights of the structures above the detector surface (Dobbins and Godfrey, 2003; Chen et al., 2007). The SAA algorithm is a common mathematical method to line up each projection image based on its calculated relative shift amount to generate reconstruction slices at certain depth. To reconstruct slice images of the object, each projection image should be shifted with an amount appropriate for the plane of reconstruction. In this paper, the shift amount was calculated along the axis of X-ray tube's motion or location based on projected locations of central points on each reconstruction plane. The shifted projection images were then added together to emphasise structures in the in-focus plane and blur out structures in other out-of-planes (Chen et al., 2007).

BP is another basic mathematical reconstruction algorithm to reconstruct three-dimensional information of the object. It also serves as the foundation of other algorithms with deblurring algorithms (Chen et al., 2007). For each pixel in the reconstruction plane, we find the corresponding projected locations in the projection images and average the pixel values to

generate reconstruction plane. The reconstructed pixel value in the tomosynthesised

reconstruction can be calculated as $(1/N) \sum_{j=1}^N I(p_j)$ where $I(p_j)$ is the pixel value at a given location on the j th projection image, and N is the total number of projection images.

We also have other tomosynthesis reconstruction algorithms available in our laboratory. In this paper, we only selected the above-mentioned representative algorithms of SAA and BP for illustration purposes. Further study is undergoing to evaluate other tomosynthesis reconstruction algorithms.

2.3 Impulse response computational analysis

With computer-simulated tomosynthesis projection images, the SAA and BP reconstruction algorithms were then implemented to reconstruct the three-dimensional images of the simulated thin wire with a reconstruction plane spacing of 1 mm. With a computer of 1.86 GHz CPU and 3 GB limited memory size, it takes less than 2 min to generate reconstruction planes.

For each reconstruction plane located at a specific Z distance away from the detector, response on the column containing the point interacted with the thin wire was identified and computed. Normalised in-plane pixel intensities in the spatial domain were computed. The normalised three-dimensional response performance was analysed and compared for different parallel imaging configurations.

3 Results

Figures 2 and 3 show the impulse response three-dimensional performance for $VA = 50^\circ$, $N = 11$ and $VA = 50^\circ$, $N = 63$, respectively. Figure 2 shows the computational analysis for SAA algorithm. Figure 3 represents the results with BP algorithm. For all plots, normalised pixel intensities in the spatial domain are displayed. The x -axis represents the sequential numbers of the reconstruction planes that are parallel to the detector surface plate. The reconstruction plane spacing is 1 mm. The y -axis represents the pixel locations of the column containing simulated wire on the reconstruction plane that is located at the centre of the simulated wire space (the wire spreads from $z = 10$ mm through $z = 40$ mm. The centre is 25 mm away from the detector face plate). The z -axis represents normalised pixel intensity equal to its grey-scale value.

One can see that with smaller number of projection images, out-of-plane artifacts are obvious in all $N = 11$ images by showing strong tails along x -axis in Figures 2(a) and 3(a). With a bigger number of projection images of $N = 63$, the out-of-plane are suppressed to a much lower level and spread to a wide range (Figures 2(b) and 3(b)). We can observe sharper in-plane peak performance for Figures 2(b) vs. 2(a) and Figures 3(b) vs. 3(a). Compared with SAA, BP showed sharper in-plane impulse response in all cases investigated (Figures 3(a) vs. 2(a), 3(b) vs. 2(b)).

4 Conclusion

Compared with the traditional two-dimensional X-ray imaging techniques, digital tomosynthesis is a novel technology to improve diagnosis of cancers and lesions. It has been demonstrated that point-by-point BP rather than SAA should be used for small structures such as micro-calcifications in breast tomosynthesis imaging (Chen et al., 2007). In this paper, we further found that, with parallel-imaging configuration, BP is also better than SAA for in-plane response and removal of out-of-plane blur artifacts, for simulated cases examined. When number of projection images increases, algorithms performed better by

showing sharper-in-plane performance. Future work will be done soon to investigate other reconstruction algorithms with different imaging configurations.

Biographies

Ying Chen is an Assistant Professor in the Department of Electrical and Computer Engineering and Biomedical Engineering Graduate Program at Southern Illinois University, Carbondale, Illinois. She received her PhD from Duke University. Her research interests include biomedical imaging, image reconstruction, digital tomosynthesis, image processing and image quality analysis.

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Figure 1.
Computer wire simulation with parallel imaging geometry

Figure 2.
Three-dimensional impulse response computational analysis of SAA: (a) SAA with $VA = 50^\circ$, $N = 11$ and (b) SAA with $VA = 50^\circ$, $N = 63$

Figure 3.

Three-dimensional impulse response computational analysis of BP: (a) BP with $VA = 50^\circ$, $N = 11$ and (b) BP with $VA = 50^\circ$, $N = 63$