

Development of tetrahedron beam computed tomography for image guided radiotherapy

Introduction: Cone beam computer tomography (CBCT) suffers inferior image quality due to scatter and other problems. We are developing a novel tetrahedron beam computed tomography (TBCT) imaging system which consists of a linear scan x-ray source and a linear x-ray detector array. TBCT system avoids the inherent problems of CBCT, thereby can significantly improve the quality of online images in image guided radiation treatment. In this paper, we describe the development of a TBCT benchtop system.

Method and Materials: A linear scan x-ray source is required in TBCT system. Our tube was manufactured by XinRay system (Research Triangle Park, NC). CNTs were used for cold cathodes and they are small enough to be organized in array [2]. Field emission electrons are generated due to the high electric field at the tip of the carbon nanotubes. The tube has 75 field emission emitters with 4 mm spacing. For the first prototype, no active cooling has been implemented in this tube. The maximum anode current is limited to 3 mA.

Fig. 1 shows the TBCT benchtop system. The linear x-ray tube and detector array are aligned perpendicular and parallel to the rotation plane, respectively. The x-ray beams are narrowly collimated into fan beams and focused onto the linear detector array. The linear detector and linear x-ray source form a 'tetrahedron' volume instead of a 'cone' volume.

We designed our own control electronics following that in ref. [2]. It was adjusted to let all the cathode currents approximately uniform at around 3mA at tube gate voltage of 2190V (But all the data following data were taken at 2060V, cathode current about 2 mA. This is to prolong the lifetime of the tube). The anode current is about 70% of the cathode current. A group of multi-slot collimators are employed to collimate the beams into fan shapes onto the detector array. Fig. 2 shows the actual collimation system.

A 5-row CT detector array was developed using silicon photodiode and CdWO₄ scintillators. The detector consists of 11 detector module boards (Fig.3) and installed on a curved frame. Each board has five 5 × 5 photodiodes arrays and the matching CdWO₄ arrays. Each photodiode pixel is a 2.54 mm square.

The scan was performed with 80 kVp and 1.3 mA 30 ms width pulsed tube current on a Catphan 600 phantom. Beam hardening correction was performed prior to image reconstruction. Scanning time is prolonged in order to compensate insufficient tube power.

We implemented both FDK and iterative image reconstruction algorithms. The Simultaneous Algebraic Reconstruction Technique (SART) was used as the algorithm for the iterative reconstruction. The projection matrix was adapted to the TBCT geometry using a distance driven approach for creating the weights. The algorithm itself can be used without modification and is given here as

$$f_j^{(n+1)} = f_j^{(n)} + \lambda \left(\frac{\sum_{i=1}^M a_{ij} \frac{(p_i - \hat{p}_i)}{\sum_{j=1}^N a_{ij}}}{\sum_{i=1}^M a_{ij}} \right),$$

where j is the image voxel, i is the detector pixel, a_{ij} is an element of the projection matrix, $p_i - \hat{p}_i$ is the difference between the measured and projected values at the i^{th} pixel, and λ is a convergence factor. The method was chosen because it has been shown in the literature to construct high quality images from noisy and undersampled data, which would also reduce artifacts caused by large cone angles in CBCT. Fig. 4 shows that the reduction in cone angle artifacts in SART when compared with images reconstructed using an FDK filtered backprojection algorithm.

Results: We measured focus spot sizes using a star pattern tool. The measurement yields a focal spot size of $0.9 \times 2.2 \text{ mm}^2$. Measurements on other emitters yielded similar results. The tube output is significantly lower than a clinical TBCT system requires. We performed phantom scan by prolonging scan time. Numerical Shep-Logan phantom was also used to evaluate image reconstruction algorithms. Fig. 4 shows digital phantom generated by FDK and iterative image reconstruction algorithms. Iterative image reconstruction does not suffer approximate cone beam image reconstruction artifact as FDK algorithms. Fig. 5 shows the CatPhan 600 images scanned by helical, TBCT and CBCT. The images produced by TBCT benchtop have much better quality than that of a commercial CBCT scanner.

Conclusion: A TBCT benchtop system has been successfully built. The multiple pixel field emission x-ray tube is fully functioning but a high tube current is desired for future clinical systems. Due to the scatter rejection mechanism, the use of high quality CT detector and iterative image reconstruction, TBCT is able to produce image quality similar to helical CT scanners.

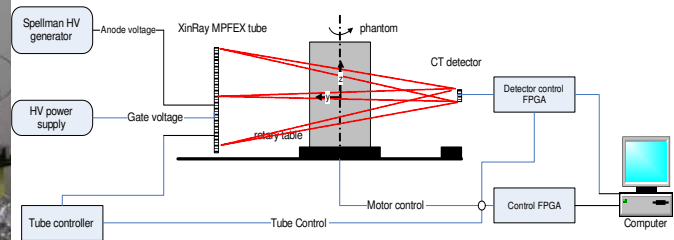
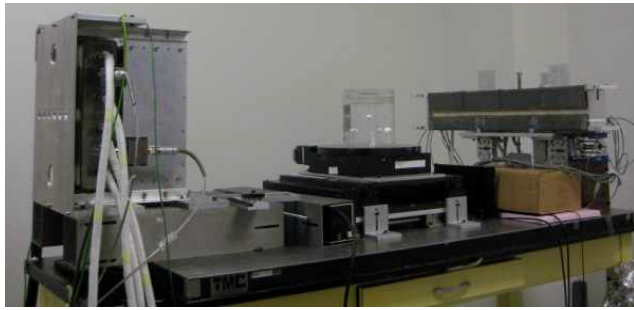


Figure 1. Left: TBCT benchtop system. Right: System connection diagram. A 75 pixel field emission x-ray tube was employed in the TBCT system.

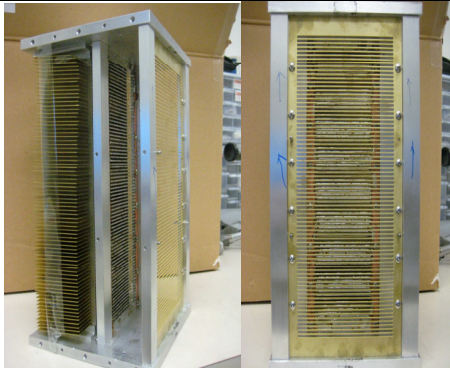


Figure 2. Multi-slot source collimator. It collimates each x-ray beam to the detector array.

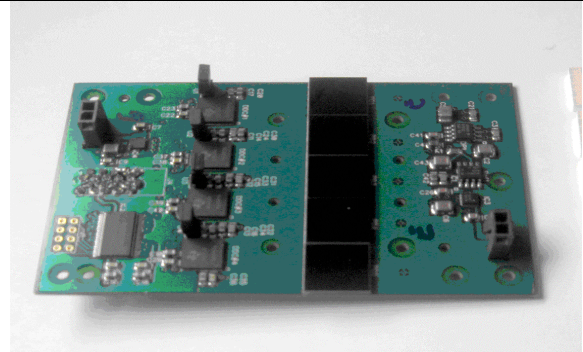


Figure 3. One of the 11 CT detector board developed using silicon photodiodes and CdWO₄ scintillators. Anti-scatter is attached on the board.

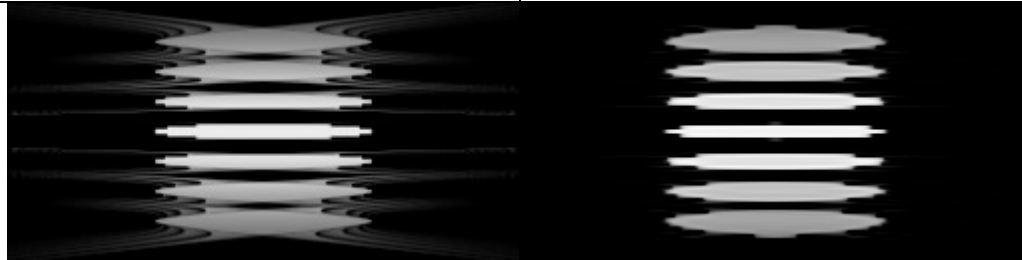


Figure 4. Comparison of FDK (left) and SAR (right) iterative image reconstruction of a numerical phantom with 7 identical disks with maximum cone angle of 12 degrees (coronal view). SAR reconstruction eliminates the approximate cone reconstruction artifact.

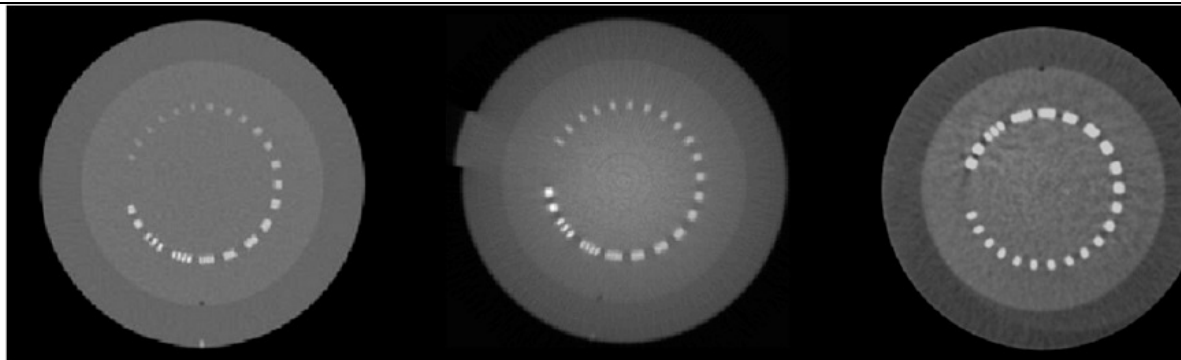


Figure 5 Comparison of TBCT image with images by commercial fan-beam helical CT (Left), TBCT (middle) and a commercial CBCT (right). In principle TBCT should produce equivalent image quality as diagnostic CT scanners.

References:

1. T. Zhang, D. Schulze, X. Xu and J. Kim, "Tetrahedron beam computed tomography (TBCT): a new design of volumetric CT system". *Phys. Med. Biol.* **54** 3365-3378 (2009).
2. J. Zhang, G. Yang, Y. Z. Lee, S. Chang, J. P. Lu and O. Zhou, "Multiplexing radiography using a carbon nanotube based x-ray source". *Appl. Phys. Lett.* **89** 064106 (2006).