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C-arm based cone-beam CT using a two-concentric-arc source trajectory: system evaluation

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Abstract

The current x-ray source trajectory for C-arm based cone-beam CT is a single arc. Reconstruction from data acquired with this trajectory yields cone-beam artifacts for regions other than the central slice. In this work we present the preliminary evaluation of reconstruction from a source trajectory of two concentric arcs using a flat-panel detector equipped C-arm gantry (GE Healthcare Innova 4100 system, Waukesha, Wisconsin). The reconstruction method employed is a summation of FDK-type reconstructions from the two individual arcs. For the angle between arcs studied here, 30°, this method offers a significant reduction in the visibility of cone-beam artifacts, with the additional advantages of simplicity and ease of implementation due to the fact that it is a direct extension of the reconstruction method currently implemented on commercial systems. Reconstructed images from data acquired from the two arc trajectory are compared to those reconstructed from a single arc trajectory and evaluated in terms of spatial resolution, low contrast resolution, noise, and artifact level.

Keywords

CT; SYS

1. INTRODUCTION

Interventional C-arm systems are now frequently equipped with flat-panel imagers and manufacturers have released clinical computed tomography products on these systems using a single arc source trajectory. Several investigators in academic environments have also implemented C-arm based cone-beam CT systems.^{1–6} Due to the utilization of a single circular arc trajectory, which is an incomplete source trajectory,⁷ cone-beam artifacts remain an inherent problem when performing volumetric reconstruction on such systems. In order to mitigate these artifacts more complex source trajectories have been proposed.^{8, 9} In this work, reconstruction from two arcs using a combined FDK-type algorithm is used, providing a significant reduction in the visible level of cone-beam artifacts. Results are

presented comparing the combined FDK-type reconstruction and conventional FDK reconstruction methods in spatial resolution, low contrast detectability, noise, and artifact level.

2. METHODS

2.1. Acquisition

All data used for results presented here were collected from an Innova 4100 C-arm system (GE Healthcare, Waukesha, Wisconsin) installed at the Clinical Sciences Center at the University of Wisconsin. A PC based data acquisition system was utilized to acquire cone-beam projection data after the gain and offset corrections were conducted, but prior to any further image processing.

The single arc acquisitions acquired on the system were accomplished using a single rotation of the C-arm about the superior-inferior patient orientation as defined by the patient table. The two arc acquisition was accomplished by angulation of the L-arm by a nominal 15° angle to either side of the patient table, as shown Figure 1(a)–(b). This source trajectory is effectively two circular arcs that are joined approximately in the center of each arc (Figure 1(c)). In all cases, the acquisition was achieved by commanding the system to travel between predefined set-points.

The detector utilized on this system is a $41\text{ cm} \times 41\text{ cm}$ flat panel detector with a maximum readout speed of 30 fps at a resolution of 10242 pixels with a size of $(400\mu\text{m})^2$ in its full field of view mode ($(400\mu\text{m})^2$ pixels binned 2×2). A second detector binning was performed before reconstruction, for an effective detector pixel size of $(800\mu\text{m})^2$. In the results presented here projection data over the central $37\text{ cm} \times 37\text{ cm}$ of the detector was used for reconstruction. The source to detector distance was set to 1200 mm, and the source to isocenter distance was 726 mm.

The experimental parameters used for all single arc acquisitions were either 70 or 95 kVp, 200 mA, 5 ms pulse width, 0.3 mm Cu added filtration, and a 13:1 anti-scatter grid. Measured half-value layer was 6.77 mm Al at 70 kVp and 8.65 mm Al at 95 kVp. The angular range of the arc was 209° , over which 420 projections were acquired. For the two arc acquisition, identical parameters were used for each individual arc, with the exception of a reduction of the current to 100 mA, to keep the total number of photons approximately constant between the single and two arc acquisitions.

2.2. Reconstruction

For both single and two arc trajectories, an FDK image reconstruction algorithm¹⁰ with Parker-type short scan weighting^{11, 12} was used. Due to slight deformations of the C-arm during acquisition, geometric correction is required to achieve optimal image quality. This was accomplished here by incorporation of conic projection matrices into the backprojection procedure.^{8, 13}

2.3. Artifact reduction

Two experimental phantoms were used to illustrate the degree of cone-beam artifact reduction possible with the combined FDK reconstruction. The first phantom was the Defrise phantom, which is known to yield severe cone-beam artifacts when reconstructed using data from a single arc trajectory. The phantom consisted of five acrylic disks 14.0 cm in diameter and 4.6 mm thick, spaced by polyurethane foam at a center-to-center spacing of 2.95 cm. Reconstructed images of this phantom are shown in Fig. 2. The second phantom was a modified Rando head phantom (The Phantom Laboratory, Salem NY). The longitudinal extent of the phantom was extended by placing Catphan modules (The Phantom Laboratory, Salem NY) between sections of the Rando phantom to illustrate robustness of the combined FDK reconstruction algorithm with respect to longitudinal truncation. Reconstructed images of this phantom are shown in Fig. 3.

As a demonstration of the the ability of the the combined FDK reconstruction to reduce artifact levels in a more clinically relevant example, a porcine animal model was scanned and reconstructed as shown in Fig. 8.

2.4. Spatial resolution and MTF measurements

To compare the spatial resolution of the single FDK and combined FDK reconstruction methods, the Catphan CTP528 high resolution module was scanned and reconstructed. Results are shown in Fig. 4. System MTF was also measured by placing a 150 μm diameter steel wire near isocenter and scanning with both acquisition modes. Twelve radial line profiles through the reconstructed wire were averaged and the wire profile was then deconvolved from the averaged measured profile.¹⁴ The Fourier transform of the resulting profile yielded the MTF curves shown in Fig. 5.

2.5. Low contrast detectability measurements

The Catphan CTP515 low resolution module was scanned and reconstructed to evaluate low contrast detectability. Results are presented in Fig. 6 for both single FDK and combined FDK acquisitions at both 70 and 95 kVp, with and without scatter correction. The scatter correction was implemented by estimating a first-order scatter profile by fitting to the scatter measured under collimator shadows, which were of 10 cm extent longitudinally on both sides of the phantom.¹⁵ The estimated scatter profiles were then subtracted from the projection data.

Noise variance in the reconstructed image was also measured by scanning a cylindrical water tank 13.5 cm in diameter and 8 cm in height. Images of the water tank were reconstructed with both single FDK and combined FDK reconstructions. Noise variance was then computed within an identical region of interest in both images.

2.6. Dose measurements

Dose measurements for both acquisitions were conducted using a 16 cm CTDI phantom and a 0.6 cc Farmer type ion chamber to make point dose measurements at longitudinally centered locations within the phantom.¹⁶ Dose was measured on the central axis and at eight peripheral locations. Total dose was calculated as the weighted sum of 1/3 of the central

dose and 2/3 of the average peripheral dose. Example plots of these measurements are shown in Fig. 7.

3. RESULTS

3.1. Artifact reduction

Reconstructed images of the Defrise phantom are shown in Fig. 2. Reconstructed voxel dimension is $(0.78 \text{ mm})^3$. Both images in Fig. 2 are displayed over the full display window, note the improved sharpness of the disks in the reconstruction from the two arc trajectory.

Reconstructed images of the modified Rando head phantom are shown in Figure 3. Reconstructed voxel dimension is $(0.39 \text{ mm})^3$ for all images. Note the improved image quality (better delineation between adjacent phantom sections and improved visualization of the air-filled cylindrical holes) in Fig. 3(f), as compared to Fig. 3(c).

3.2. Spatial resolution

Reconstructed images of the Catphan CTP528 high resolution module are shown in Fig. 4(a) for the single arc acquisition and Fig. 4(b) for the two arc acquisition. Pixel dimension is $(0.39 \text{ mm})^2$, slice thickness is 10 mm. Zoomed reconstructions of the 8 to 10 lp/cm section of the Catphan CTP528 high resolution module are shown in Fig. 4(c) for the single arc acquisition and Fig. 4(d) for the two arc acquisition; pixel dimension is $(0.09 \text{ mm})^2$. The limiting system resolution with the single FDK algorithm is approximately 9 lp/cm. The resolution using the combined FDK reconstruction method is similar, although slightly lower. Additional measurements indicate that the small degradation in resolution when combining the two volumes for the final reconstruction is due to experimental limitations with the current method of positioning control for the two different L-arm positions, rather than an inherent limitation in system accuracy or reconstruction method.

A comparison of the MTF of both reconstruction is shown in Fig. 5. The conventional FDK reconstruction MTF is plotted as a dashed blue line and the combined FDK reconstruction MTF is plotted as a solid green line.

3.3. Low contrast detectability

Fig. 6 shows reconstructed images of the Catphan CTP515 low contrast module. Fig. 6(a) and 6(b) show results for 70 kVp scans with conventional FDK and combined FDK reconstruction, respectively. Fig. 6(e) and 6(f) show results for 70 kVp scans with conventional FDK and combined FDK reconstruction, respectively, with scatter correction included. Fig. 6(c) and 6(d) show results for 95 kVp scans with conventional FDK and combined FDK reconstruction, respectively. Fig. 7 6(g) and 6(h) show results for 95 kVp scans with conventional FDK and combined FDK reconstruction, respectively, with scatter correction included. Pixel dimension is $(0.78 \text{ mm})^2$ and slice thickness is 10 mm for all images. Both reconstruction methods show similar visibility of the 1% inserts.

Noise variance in the reconstructed image was measured by scanning a cylindrical water tank. Reconstructed voxel dimension was $(0.39 \text{ mm})^3$. For both the conventional and combined FDK reconstruction methods, the mean reconstructed voxel signal value was

0.0215. The measured variance was 2.53×10^{-7} and 2.33×10^{-7} for the conventional FDK and combined FDK based reconstructions, respectively. Given that the total mAs is equal in both scans, the near equivalence in noise level is to be expected.

3.4. Dose measurements

Measured dose was 5.67 mGy and 5.62 mGy for single and two arc scans at 70 kVp, respectively. Measured dose was 17.5 mGy and 17.3 mGy for single and two arc scans at 95 kVp, respectively. Fig. 7(a) shows comparisons of dose measurements for a 70 kVp single arc scan (blue) and the summed contribution for the two arc scan (red). The individual contributions from both segments of the 70 kVp two arc scan are shown in Fig. 7(b). The agreement between the average doses for the single and two arc acquisitions is expected since the total mAs was equal in both acquisitions.

3.5. In-vivo results

Reconstructed images of the porcine animal model are shown in Fig. 8. Conventional FDK reconstruction is shown in (a) and combined FDK reconstruction is shown in (b). Lower levels of vertically-oriented streaking artifacts can be observed in regions surrounding the teeth and bones. Reconstructed voxel dimension is $(0.39 \text{ mm})^3$. Angular streaks in the upper and lower left corners of the combined FDK reconstruction are truncation artifacts, which are present since the supported volume for reconstruction is slightly smaller for two arc case than for the single arc case. As these artifacts occur only near the edges of the field of view, no effort was made here to reduce them. These magnitude of these artifacts could be reduced with standard truncation correction schemes, or by simply slightly reducing the reconstruction field of view.

4. CONCLUSION

A combined FDK reconstruction method has been used with a source trajectory of two arcs to reduce cone-beam artifact levels. For an angle of 30° between the two arcs, the combined FDK reconstruction provides a significant reduction in cone-beam artifact levels as compared to a single arc reconstruction, while providing otherwise comparable image quality at equal dose. The use of a combined FDK reconstruction method would ease implementation on clinical systems, as it is a simple extension of commercially implemented methods.

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Figure 1.

The positioning arm parked at 15° (a), where the gantry spins along the path denoted by the solid arc. The positioning arm parked at -15° (b), where the gantry spins along the path denoted by the dashed arc. The complete source trajectory generated by these two motions of the C-arm gantry (c).

Figure 2.
Reconstructed images of the yz plane at $x=-0.39$ mm for the Defrise phantom using a conventional FDK reconstruction (a), and a combined FDK reconstruction (b).

Figure 3.

Reconstructed images of the modified Rando phantom: (a) and (d) are xz slices at $y=23.05$ mm using conventional and combined FDK reconstruction, respectively; (b) and (e) are yz slices at $x=20.70$ mm using a conventional and combined FDK reconstruction, respectively. Note the improvement in image quality for the combined FDK reconstruction in the regions indicated by the arrows. Enlargements of the lower left corner of the yz slice presented in (b) and (e) are displayed in (c) and (f).

Figure 4.

Reconstructed images of the Catphan CTP528 high resolution module are shown in (a) for conventional FDK reconstruction and (b) for the combined FDK reconstruction. Zoomed reconstructions of the 8 to 10 lp/cm section of the Catphan CTP528 high resolution module are shown in (c) for conventional FDK reconstruction and (d) for the combined FDK reconstruction.

Figure 5.

Measured MTF for the two reconstruction methods. The dashed blue line is the conventional FDK reconstruction MTF and the solid green line is the combined FDK reconstruction MTF.

Figure 6.

Reconstructed images of the CTP515 low contrast module. (a) and (b) show results for 70 kVp scans with conventional FDK and combined FDK reconstruction, respectively. (e) and (f) show results for 70 kVp scans with conventional FDK and combined FDK reconstruction, respectively, with scatter correction included. (c) and (d) show results for 95 kVp scans with conventional FDK and combined FDK reconstruction, respectively. (g) and (h) show results for 95 kVp scans with conventional FDK and combined FDK reconstruction, respectively, with scatter correction included.

Figure 7.

Comparison of dose measurements for a 70 kVp scan. Measurements from a single arc scan (blue) and the summed contributions from the two scan (red) are shown in (a). The individual contributions from the 70 kVp two arc scan, as well as central and average doses, are shown in (b).

Figure 8.
Reconstructed xz slice at $y=4.9$ mm of a porcine model using conventional FDK reconstruction (a), and combined FDK reconstruction (b).