X-ray micro-CT with a displaced detector array: Application to helical cone-beam reconstruction

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In x-ray micro-CT applications, it is useful to increase the field of view by offsetting a two-dimensional (2D) detector array. In this technical note, we briefly review the methods for image reconstruction with an asymmetric 2D detector array, elaborate on the use of an associated weighting scheme in the case of helical/spiral cone-beam scanning, and perform a series of numerical tests to demonstrate helical cone-beam image reconstruction with such an arrangement. © 2003 American Association of Physicists in Medicine. [DOI: 10.1118/1.1609058]

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Given various sizes of objects in x-ray micro-CT applications, it is desirable to adjust the field of view of a scanner by displacing a detector array. A popular way to do so is to offset a detector array by 50%, doubling the diameter of a field of view. Recently, Wang proposed a general scheme to displace a detector array by a factor between 0% and 50% for a continuously adjustable field of view. Specifically, his proposal was formulated in a generalized Feldkamp framework that allows helical cone-beam geometry, as shown by Formula (5) in Ref. 1, although the numerical simulation was only performed for circular fan-beam and cone-beam geometry. Since then, some discussions with colleagues have occurred, which indicate a substantial benefit of elaborating on the unique features of this formula, and comment on relevant work previously not cited in Ref. 1.

In this technical note, we review the detector displacement techniques, report the use of an associated weighting scheme in the case of helical cone-beam scanning, and perform a series of numerical simulations with the 3D Shepp-Logan phantom to demonstrate helical cone-beam image reconstruction with a displaced detector array.

Silver et al. (Bio-Imaging Research, Inc., Lincolnshire, IL) supplied a CT-option to a Philips radiation therapy simulator. It used three displaced detector positions, corresponding to offsets of 0%, 25%, and 45%, respectively. The redundant data were feathered, similar to what was described in Ref. 1. Furthermore, they corrected the problem of photon flux drifting, as there was no reference detector available. They reported these results for the case of circular fan-beam scanning in 1994 as a poster and an abstract. Although there is no mention in the abstract of detector displacement, it has been confirmed by Silver that such a scheme was implemented in commercial fan-beam systems.

Bruning et al. (TeraRecon, Inc., San Mateo, CA; EXXIM Computing Corp., Livermore, CA) used essentially the same weighting scheme in the circular cone-beam scanning case, and found that it worked well. Voxels far above or below the equatorial plane, however, appear to contain some artifacts caused by inconsistencies between quasi-opposite rays. This is similar to the case of half-scan cone-beam reconstruction. They also studied artifact correction in this context. However, they have not published their results.

La Riviere et al. (University of Chicago, Chicago, IL) developed two methods for asymmetric fan-beam transmission CT. The first method, called the hybrid approach, is based on a Fourier-based rebinning of fan-beam data. The second method is a generalized fan-beam filtered backprojection algorithm, which is similar to the fan-beam application suggested in Ref. 1. The authors have not, however, considered the asymmetric cone-beam detector configuration.

Actually, the use of a displaced detector array has been suggested before in the literature for cone-beam reconstruction in the circular cone-beam scanning case. Therefore, the primary contribution of Ref. 1 is the extension of asymmetric cone-beam image reconstruction from the circular scanning case to the helical scanning case. This situation is comparable to the generalization of the Feldkamp algorithm from the circular scanning case to the helical scanning case. In the following, let us focus on the helical cone-beam image reconstruction using a displaced two-dimensional (2D) detector array in the framework of Ref. 1. Note that when the scanning locus is not exactly a helix, the weighting functions in Refs. 1 and 4 must be accordingly modified so that weights on pairs of redundant or quasi-redundant data are summed to one.

We illustrate the helical cone-beam geometry in Fig. 1, where elements of the 2D detector array are organized equi-spatially, and should be scaled to go through the origin of the reconstruction system so that they may be used with our generalized Feldkamp formula. Note that the detector array is displaced in this figure to enlarge the field of view. In Fig. 2, a cross-section through the reliable region of reconstruction is illustrated, where voxels are radiated from a sufficiently large angular range for satisfactory image reconstruction. To reconstruct any voxel, it is required that the projection angular range of cosine-corrected truncated cone-beam data be equivalent to that of fan-beam data with a one-dimensional displaced detector array. In Fig. 3, the reli-
able region of reconstruction is shown as a three-dimensional illustration. Given a radius $r$ of a specimen, it can be proved that to have a nonempty cross-section the helical pitch $H$ must satisfy the following inequality:

$$0 < H < \frac{2\Pi (R + r)}{R + S}.$$  \hspace{1cm} (1)

where $2\Pi$ represents the height of the 2D detector array, $R$ the distance between the source and the longitudinal axis of the reconstruction system, and $S$ the distance between the detector and the longitudinal axis. In the $H$ range (1), the size of the cross-section can be expressed as follows:

$$l = \min \left\{ R + r - \frac{H(R + S)}{2\Pi}, \frac{2\Pi}{2} \right\}.$$ \hspace{1cm} (2)

In our numerical simulation with a displaced detector array, the generalized Feldkamp algorithm is developed in C on an SGI O2 workstation. The 3D Shepp and Logan phantom, which is approximately spherically shaped with a diameter of about 2 (mathematical unit), is used as the test object. The source-to-origin distance is 5. The size of the detector array is 2.2 by 2.2 with 256 by 256 cells, whose center is at the origin of the reconstruction system. The number of projections is 200. Various helical pitches and detector offsets are tested. Transverse images are reconstructed on 256 by 256 matrices. The pixel values are linearly transformed with necessary truncation from $[0.95, 1.1]$ into 256 levels for better visualization.

Figure 4 shows the images reconstructed at $z = -0.25$ and $z = 0.625$ using the generalized Feldkamp algorithm with a regular detector array setting and a 30% offset detector array for 0.2 and 1.0 pitches, respectively. Note that in all these cases the $z$ location of the central view of projections is made the same as that of the corresponding slice. It is observed in our simulation that the images reconstructed using the proposed weighting scheme do not differ much visually from the traditional reconstructions, if (1) the helical pitch is not too large ($<0.5$), or (2) the structures under reconstruction do not change too much longitudinally ($|z| < 0.5$). However, when neither of these two conditions is met, there are some shading artifacts as shown in Fig. 4(h).

The approach we have used in this project only leads to approximate reconstruction. In the case of a 2D displaced detector, it was mentioned by Silver that reflected data usually have different cone angles. This fact complicates the Feldkamp-type cone-beam reconstruction. Nevertheless, it is found in our simulation that good quality images could indeed be obtained in most cases.

Our above-mentioned scheme for enlargement of the field of view is not only useful for micro-CT applications, but also...
valuable for clinical CT. It is not unusual that flat panel detectors are not sufficiently large to cover the full body. Hence, the method of asymmetric detector positioning can be used in that context. Another way to increase the field of view is to use synthetic detector arrays, as discussed before in circular cone-beam geometry. That idea can be extended to helical cone-beam geometry as well. Finally, as shown in Fig. 3, the reliable region of reconstruction associated with a detector-displaced helical scan is a twisted structure. Interestingly, reliable regions associated with two appropriately designed helical scans can be seamlessly combined into a perfect cylindrical object support.

In addition to the preconvolution weighting technique described in Refs. 1 and 4, two other methods for cone-beam CT from width-truncated projections were also considered in Ref. 4. They are (1) postconvolution weighting after estimation of missing data, and (2) heuristically formulated iterative reconstruction. Although it was shown in numerical simulation that the postconvolution weighting method requires a smaller over-scan range ($\sigma$ in Fig. 1) than the preconvolution weighting method, the former method extends measured data nontrivially, and increases the computational complexity significantly. On the other hand, when a zero over-scan range must be handled, a voxel-driven rebinning subroutine can always be evoked to organize cosine-corrected cone-beam data into a complete set of parallel-beam projections for Feldkamp-type reconstruction. Alternatively, well-established iterative algorithms, such as the EM and SART algorithms, can be used for cone-beam reconstruction, each of which converges at a substantially higher computational cost.

In conclusion, we have studied the cone-beam imaging mechanism that allows both a displaced 2D detector array and a helical scanning locus, and demonstrated the feasibility

![Fig. 4. Numerical simulation of spiral cone-beam CT using the generalized Feldkamp algorithm with a regular detector array setting and a 30% offset detector array, respectively. (a)–(f) For the slice $z = -0.25$, while (g)–(l) are for the slice $z = 0.625$. The left column images correspond to the reconstructions with a full detector array, while the right column ones with the offset detector array. (a), (b), (g), and (h) are with a pitch of 0.2, while (c), (d), (i), and (j) with a pitch of 1.0. (c) and (f) $10\times$ magnified absolute values of (a)–(c) and (b)–(d) while (k) and (l) show $10\times$ magnified absolute values of (g)–(i) and (h)–(j), respectively.](image-url)
of such an approach in numerical simulation. This technique is of practical value for micro-CT and clinical CT applications.

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