



Streak Preventive Image Reconstruction with ART and Adaptive Filtering

RANGARAJ M. RANGAYYAN, MEMBER, IEEE, AND RICHARD GORDON, MEMBER, IEEE

Abstract—Streaks arise in computed tomograms for a variety of reasons, such as presence of high-contrast edges and objects, aliasing errors, patient movement, and use of very few views. The problem appears to be an inherent difficulty with all reconstruction methods, including backprojection (with convolution) and the algebraic reconstruction technique (ART). This paper presents the derivation and results of an ART-like algorithm (SPARTAF) oriented towards prevention of streaks via optimization of a cost function based on features of streaks, subject to the constraints of the given projection data. The object-dependent method employs pattern recognition of streaks and adaptive filtering during iterative reconstruction by ART. Results of experiments with a test pattern and of application of the method to reconstructive tomography from radiographic films are presented and the convergence properties demonstrated.

INTRODUCTION

STREAK-LIKE artifacts arise for a variety of reasons in reconstructions made from projections. There have been a few studies on the causes of such artifacts in computed tomography and correction procedures to remove streaks have also been proposed. Some of the causes of streaks studied are the "exponential edge-gradient effect" [1], the presence of out-of-field objects [2], opaque objects leading to saturated rays [3], movement of objects during scanning, and the use of incomplete projection data [4], [5]. Aliasing error caused by inadequate

sampling of the projection data is yet another cause of streaking [6], [7]. Although the software and mathematics of reconstruction are known to have this inherent weakness [8]–[10], the methods proposed to overcome streaking have only been postreconstructive cleaning-up procedures (for example, [11]) and preprocessing of projection data (for example, [1], [3], [6], [12]). A few other studies on reconstruction artifacts are listed in [13]–[18]. This paper deals with prevention of streaks caused by the use of very few views and the presence of high-contrast objects and edges.

We found that a suitable modification to the reconstruction procedure that would *prevent* streaks from getting into the reconstruction is a better approach than trying to remove them after they have already been introduced (see [19], [20] for details of our initial work along these lines). We present here the derivation and results of an ART-like algorithm with this approach in mind, called SPARTAF (streak preventive ART with adaptive filtering). Pattern recognition of streaks and adaptive filtering using directional neighborhood operators are employed during iterative reconstruction by ART. The operations are optimized by minimizing a cost function based on the features of streaks, subject to the constraints of the given projection data. Reconstructions of a test pattern are presented demonstrating the performance of the algorithm. Performance of the algorithm with real data is illustrated by examples from our work on computed tomography from a few radiographs for teleradiology [21], [22]. Our method could lead to significant dose reduction by reducing the number of views taken in CT scanners. Since only a few views can be obtained in many industrial applications of computed tomography, the algorithm should be of considerable use in

Manuscript received April 2, 1982; revised December 6, 1982. This work was supported in part by a Strategic Grant from the Natural Sciences and Engineering Research Council of Canada and by grants from the Control Data Corporation and the Manitoba Medical Services Foundation.

R. M. Rangayyan is with the Department of Electrical Engineering, University of Manitoba, Winnipeg, Man., Canada R3T 2N2.

R. Gordon is with the Departments of Pathology, Radiology, and Electrical Engineering, University of Manitoba, Winnipeg, Man., Canada R3E 0W3.

nondestructive testing. It should also find applications in electron microscopy [23], where electron beam damage of macromolecules limits the number of useful exposures and thus, views, that can be obtained, and in computed mammography from films, where the number of views is limited by dose considerations.

THE ALGEBRAIC RECONSTRUCTION TECHNIQUE

The algebraic reconstruction technique (ART) is an iterative procedure which starts with an initial estimate of the picture and updates the pixels so as to satisfy the given projection data. A brief description of ART from a digital picture processing point of view is given below; for more detailed analysis of ART and other reconstruction algorithms, see [24]–[26].

The image reconstruction problem can be posed as follows. Given a set of projections $R(l, k)$ at angles θ_l , for P views ($l = 1 \cdots P$), each view having $2R + 1$ rays ($k = -R \cdots R$), compute a picture $p(i, j)$ such that the ray sums $S(l, k)$ of $p(i, j)$ are as close to $R(l, k)$ as possible. The ART algorithm updates pixels belonging to individual rays of a view to meet the ray sum criterion as

$$p^{q+1}(i, j) = p^q(i, j) + (R(l, k) - S^q(l, k))/N(l, k) \quad (1)$$

where $N(l, k)$ is the number of pixels in the ray (l, k) and q refers to the iteration number. The above operation performed over all views constitutes one cycle, and a number of such cycles will have to be executed before all ray sums are met. A suitable convergence criterion can be set up based on the error of reconstruction, defined as

$$E^q = \sum_l \sum_k |R(l, k) - S^q(l, k)| / (MP) \quad (2)$$

where M is the number of pixels in the image and P is the number of projections used. The initial picture is usually uniformly gray, of intensity equal to the average brightness of the picture, which may be computed from the given projection data.

Equation (1) represents additive ART, so called because the correction applied is additive. As this can lead to negative values being assigned to pixels, an additional constraint is essential. This is done by setting the pixel to zero whenever the value given by (1) is negative.

The multiplicative version of ART is defined as

$$p^{q+1}(i, j) = p^q(i, j) R(l, k) / S^q(l, k) \quad (3)$$

which has the advantage that negative pixel values are not encountered (for nonnegative ray sums).

We define the ray width at different projection angles as

$$r_l = \max \{ |\cos(\theta_l)|, |\sin(\theta_l)| \} \quad (4)$$

so that each ray crosses one and only one pixel per row or column. This way, a plot of the number of pixels crossed versus the ray number would be smooth. Fig. 1 gives a representation of the ray geometry used.

We use a simple digital test pattern to demonstrate the performance of ART and the new algorithm being derived. The original test pattern is given in Fig. 2(a) (101×101 matrix, pixel values 25 and 255). Reconstruction of the test pattern by multiplicative ART with eight views at $20, 40, \dots, 160$ degrees (measured along the rays) is given in Fig. 2(b). The num-

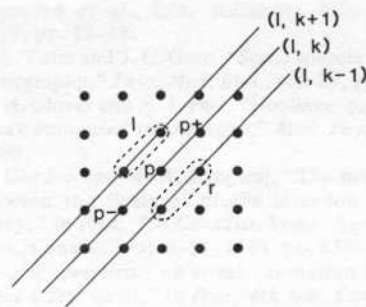


Fig. 1. Reconstruction ray geometry.

ber of iterations was fixed at five for the sake of comparison. A total of 220 rays ($k = -110 \cdots 110$) were used in each view, to first compute the projection data, and then reconstruct the image. The reconstruction clearly demonstrates streaks at all projection angles.

FEATURES OF STREAKS

Linear streaks usually occur only along the rays used in reconstruction. The most common cause of streaks is the presence of high-contrast edges and objects in the image. The fundamental reason for streaking, however, is that the reconstruction algorithms (both backprojection and ART) have a "smearing" feature—the ray sum, or the correction in the case of ART, is spread out uniformly along the path of the ray. The streaks so introduced are usually not corrected by the subsequent iterations. The use of a very large number of views tends to merge the streaks at different angles and give a uniform background. When the number of views used is small, as in our experiments, the streaks remain obvious, as can be readily seen in Fig. 2(b).

A study of the streak patterns in Fig. 2(b) points to two types of streaking mechanisms—the smearing of the larger (whiter) ray sums leads to the broad streaks which are whiter against the light background (transmission type), and, at the edges of the high-contrast objects, dark tangential streaks arise due to compensations made in the background for whiter values assigned to pixels at the boundaries of the objects (compensatory type). While the transmission type of streaks are easily smoothed out by the use of a large number of views, the compensatory streaks are not.

Treating the pixels of a ray as forming a scan-line signal, we may characterize a streak by a high autocorrelation between successive pixels along the ray. In terms of local contrast, the contrast between adjacent pixels along the ray scan line would be low, whereas the contrast between neighboring pixels belonging to the streaking ray and the adjacent rays would be high. We use these features for detection of nascent streaks during reconstruction and also to decide the type of filter to be employed for suppression of these artifacts and reconstruction of the image.

OPTIMIZATION OF NEIGHBORHOOD OPERATIONS AND ADAPTIVE FILTERING

As linear streaks ordinarily occur only in the directions of the rays used for scanning, we felt that a suitable criterion based on pixels belonging to adjacent rays, when incorporated

