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Noise reduction for low-dose X-ray CT based on fuzzy logical in stationary wavelet domain

Yi Liu, Zhiguo Gui*, Quan Zhang

National Key Laboratory for Electronic Measurement Technology, North University of China, Taiyuan 030051, China

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ABSTRACT

Apparent streak-like artifacts will present in reconstructed images due to excessive quantum noise in low-dose X-ray imaging process. Dealing with the noisy sinogram before a filtered back-projection (FBP) is a useful solution to solve this noise problem. In this paper, we proposed a novel noise restoration method combining wavelet and fuzzy logical technology for low-dose computed tomography (CT) sinogram. The method first utilizes stationary wavelet transform on the noisy sinogram, namely decomposes the sinogram to different resolution levels. And then, at each decomposed resolution level, a fuzzy shrinkage filter is applied to restore the noise-contaminated wavelet coefficients. Simulations were performed and indicated that the proposed method could significantly suppress noise and reduced streak-like artifacts in reconstructed images while at the same time maintaining the image sharpness.

1. Introduction

X-ray CT has been widely applied to medicine field and shown effective actions in several types of tissue such as brain, bone and soft tissue. High-dose, which is harmful to patients, may lead to adverse health effects, and that's why there is a growing awareness of the significance of minimizing the radiation dose delivered to patients during X-ray CT [1]. Therefore, more and more scholars have applied themselves to the study of low-dose CT imaging. In this kind of study, what needs attention is that X-ray reconstructed images will be severely degraded because of the quantum noise which comes from the low-dose scanning. Streak-like artifacts appear most frequently in bony structures at the base of the skull and petrous bone regions because these dense structures are only partially included in the slice, resulting in partial volume effect and high contrast errors. Thus, how to suppress noise and remove streak-like artifacts in reconstructed images has recently become a hotspot.

Noise reduction in sinogram space before FBP has been an effective way to deal with this problem since FBP is simple and fast. In the previous study of Elbakri et al. [2,3], the detected photon numbers are considered to follow a Poisson distribution plus a background Gaussian noise with zero mean. A penalized Poisson likelihood maximization algorithm was then proposed. Later, Whiting et al. [4] proposed a compound Poisson distribution model, which takes both the characteristics of the energy-integrating sensors in the X-ray CT detector and the energy spectrum of X-ray beam into account. Li et al. [5–7] consider that noise in the low-dose CT sinogram after logarithm transform and calibration could be modeled as a signal-dependent variable and the sample variance depended on the sample mean by an exponential relationship. And then the penalized weighted least-squares (PWLS) approach was applied to the noisy sinogram, thus, the optimal estimation of the projection data was obtained for FBP reconstruction. Jianhua Ma [8] designed a generalized Gibbs prior that exploited nonlocal information of the projection data and used the FBP method to finish the final CT reconstruction. Chen et al. [9] studied the Bayesian statistical reconstruction for low-dose X-ray CT using an adaptive-weighting nonlocal prior and got a satisfactory effect. To obtain a more accurate model, Yuan-ke Zhang [10] studied the property of the projection data and found an important character that isolated noise points may exist in some areas of the sinogram. In his study, the projection data approximately follows the non-stationary Gaussian distribution after the isolated noise points are removed.

Recently, wavelet transformation in the field of image denoising has achieved great success and has good effectiveness for the multi-scale image denoising [11,12]. We pay attention to the fact that the wavelet analysis has been applied to the sinogram for the CT imaging because of its multi-scale: Zhong [13] presented WCMS (Wavelet coefficient magnitude sum) in 2004 and his experiments showed that 60% of the noise could be removed. Wang Dong-ming et al. [14] proposed WCLA (Wavelet Coefficient Local adaptive) for the noisy sinogram and their method was proved to be effective in removing noise while maintaining the diagnostic image details.

* Corresponding author at: North University of China, Taiyuan 030051, China. Tel.: +86 0351 3557226; fax: +86 0351 03557226.
E-mail address: gzgtg@163.com (Z. Gui).

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Wang [15] proposed a multiscale penalized weighted least-squares sinogram restoration method for low-dose CT, and this method adaptively removes non-stationary noise.

In this paper, we study a development of a multi-scale noise reduction algorithm for low-dose CT using fuzzy logic shrinkage function since fuzzy logic is also a useful tool for image processing. The proposed method accomplish noise reduction of Low-dose CT projection data by combining wavelet and fuzzy logical. Noise and streak-like artifacts in the reconstructed images can be removed through restoring the noise-contaminated wavelet coefficients. The fuzzy shrinkage filter in fact adjusts the wavelet coefficients of the projection and makes them close to the ideal coefficients. From experimental comparisons, it has been show that this proposed method can suppress noise, remove streak-like artifacts effectively, and preserve edges without excess smoothing.

1.1. Noise character of low-dose CT

Wang [5,15] expounded the noise modeling of the projection data: the projection data after system calibration and logarithm transformation is approximately Gaussian distributed in low-dose CT applications. And a non-linear dependency between sample mean and variance can be described as follows.

$$\sigma_{P_i}^2 = f_i \exp\left(\frac{\bar{p}_i}{\eta}\right) \tag{1}$$

where $\overline{P_i}$ and $\sigma_{P_i}^2$ is the mean and variance at detector bin i. η is a scaling parameter which is object-independent but completely determined by the system settings and f_i is a parameter adaptive to different bins.

It is obviously seen that noise in the projection space is non-stationary Gaussian noise. Considering its non-stationarity, it is more difficult to remove noise with conventional filters which have limited capacity for such non-linear and non-stationary noise.

Zhang Yuan-ke [10] and Chen Liwen [16] studied the attribution of low-dose CT data after wavelet transform, finding that non-stationary noise in wavelet space is consistent with that in time space, and proved that it is reasonable to remove non-stationary noise by restoring wavelet coefficients in wavelet space. Therefore, further study for restoring low-dose CT sinogram using wavelet analysis in our paper is reliable.

2. Methods

2.1. Wavelet transform and fuzzy logical

Multi-resolution analysis makes signal features present at different scales or resolutions. It is easy to characterize the gross features in a large "window" and the local features in a small "window" [17]. Since images are two-dimensional, wavelet transform should be extended to two-dimensional. And since Mallat [18] proposed fast wavelet transform (FWT), multi-resolution analysis for images has become computationally efficient. In this paper, we chose the discrete stationary wavelet transform (DSWT) and applied it to the noisy sinogram. As discussed in [19], DSWT is a non-orthogonal wavelet transform in which the length of approximation signal and detail signals have the same length as the original signal. This proposed method also applies fuzzy logical to design a shrinkage function, since fuzzy logical has been proved useful for image processing. The fuzzy shrinkage function on one hand well inhibits the Gibbs phenomenon which results from orthogonal wavelet threshold processing, on the other hand well preserves edges with good visual effect. One key point of this proposed method is how to select a suitable wavelet basis function and an appropriate decomposition level. And this point will be expounded in the following text.

2.2. Selection of wavelet basis function

Different wavelet bases have different time–frequency characteristics and generate different results. How to select a suitable wavelet basis function is very critical to implement wavelet algorithms and which wavelet basis function will be used depends on the application. For low-dose CT, stronger relativity exists between adjacent projections, therefore orthogonal wavelet is chosen because it is able to simplify the calculation process, especially makes the coefficients between inner and external scales have small relevance after wavelet decomposition. In addition, the wavelet selection is affected by the shift variance, regularity and number of vanishing moments. In this paper, we selected the sym2 wavelets for computer analysis and simulations since symlets(symN) wavelets have the characters of regularity, orthogonality and compact support.

2.3. Proposed methods

Stationary wavelet transform decomposes the sinogram into stationary and non-stationary bands. In fact, for low-dose CT sinogram, local high noise seriously pollutes coefficient details with the fact that only high frequency coefficients are mainly contaminated, while low frequency coefficients are lightly contaminated. Therefore only high frequency coefficients need to be processed meanwhile approximation coefficients remain unchanged.

Wavelet thresholding method which is first proposed by Donoho and Johnstone [20,21] adjusts wavelet coefficients based on the amplitude characteristics. Classical wavelet thresholding methods mainly include three algorithms: hard thresholding, soft thresholding and semi-thresholding methods. However, this kind of method is based on the assumption that noise is independently normal distributed and the final denoising performance mainly depends on the threshold. Therefore, for the non-stationary Gaussian noise in the low-dose CT sinogram, the results of classical thresholding methods are not satisfying.

We note that the sinogram actually constitutes of one and one line which represents projection and this property reveals the fact that there are no obvious uniform regions and edges are relatively vague. And this property also can be reflected in the wavelet domain and motivated by the conclusion that has been obtained by Zhang Yuan-ke and Chen Liwen. Thus, it is reasonable to utilize fuzzy logical to analysis the sinogram after wavelet transform. Then in this paper, a fuzzy shrinkage function is proposed to replace the classical threshold filters in the wavelet domain.

Within high frequency sub-bands at each level, wavelet coefficients are analyzed and segmented into highly textured region and weakly textured region using fuzzy membership function defined in Eq. (2). This equation map wavelet coefficients into the interval [−1,1], which to some extent can be regarded as a generalized fuzzy interval.

$$\mu^j = \frac{w_{\text{old}}^j}{\text{MAX}} \quad \text{MAX} = \max\left\{\left|w_{\text{old}}^j\right|\right\} \tag{2}$$

where w_{old}^j is the high frequency coefficient including the horizontal, vertical and diagonal directions at level j, and the absolute value of μ^j ($|\mu^j| \in [0,1]$) represents the degree that belongs to image signal according to the wavelet denoising theory.

The proposed fuzzy shrinkage function, defined in Eq. (3), subsequently is used to adjust the fuzzy membership values for each