Improved Metal Artifact Reduction Method for X-ray CT Achieved by Reducing the Effect of Interpolation Errors

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Abstract
This paper deals with the metal artifact problem in X-ray computed tomography (CT). If an X-ray opaque structure (metal object) is present in the region to be examined, metal streak artifacts may appear in the reconstructed image, resulting in a non-diagnostic image. In traditional analytical metal artifact reduction (MAR) methods, the part of the projection data affected by the metal object is removed from the original projection data, and the removed part is filled in by interpolation. Then, an image is reconstructed from the interpolated projection data using the filtered back-projection (FBP) algorithm. These methods can considerably reduce metal streak artifacts, but a satisfactory image still may not be reconstructed due to interpolation errors. It is known that the interpolation errors which arise during the interpolation step lead to DC-shift and shading artifacts in the reconstructed images. In the FBP-type MAR algorithm, the interpolated projection data is filtered using a non-local ramp filter before back-projection, which propagates the interpolation errors to the whole projection data. In this paper, we propose a differentiated back-projection (DBP)-type MAR method to reduce the effect of interpolation errors and consequently reduce DC-shift and shading artifacts. We expect image quality to be improved by the proposed method because the DBP reconstruction algorithm is able to apply non-local filtering after back-projection along the preferred Hilbert filter direction. This property helps to reduce the propagation of interpolation errors. A simulation study was performed to evaluate the proposed method.

Key words: X-ray CT, Image reconstruction, Metal artifact, Interpolation error

1. Introduction
Thanks to the development of advanced medical treatment technologies, the metallic implanted medical treatment is not only limited to dental filling, but also extends to cardiac pacemaker, implanted marker, and so on. However, when a CT examination is applied to a metallic implanted patient, the metal artifact problem occurs in the reconstructed CT image. Because the attenuation coefficient of the metallic implant is much larger than those of surrounding soft tissues, little or almost no X-rays can pass through the metallic implant in the patient body with the X-ray energy used in ordinary medical CT scanners. As a result, some part of the acquired projection data corresponding to the metal object takes significantly large values. If we directly use such projection data in image reconstruction, it would lead to a low-quality CT image degraded with the metal artifacts. We show a typical example of the metal artifacts in Fig. 1. In order to achieve acceptable image quality in such cases, during the past decades, a number of image reconstruction and compensation methods have been proposed to tackle the metal artifact problem. Generally, these methods can be categorized into the following two classes. The first class includes model-based iterative reconstruction algorithms [1~3], and the second class includes analytical reconstruction algorithms combined with various compensation techniques [4~6]. The iterative methods allow to easily utilize a prior
knowledge of the object to be imaged and statistical noise properties to reduce the metal artifacts. However, the iterative methods require a large computing time and a large memory storage, and they are rarely used in practical CT scanners.

Among the analytical algorithms, the filtered back-projection (FBP) algorithm combined with an interpolation to smoothly fill the metal contaminated part of projection data is a simple way to achieve the metal artifact reduction (MAR). The processing steps of this method is briefly summarized as follows. First, we identify the metal contaminated part of projection data and smoothly fill the contaminated part by using various interpolation techniques from the neighboring uncontaminated projection data. The polynomial interpolation [7], wavelet interpolation [8], and linear prediction [9] have been proposed to smoothly fill the contaminated part of projection data. Second, CT images are reconstructed from the completed projection data by using the conventional FBP algorithm. Up to now, research on the MAR focuses on the first step, and there exist few literatures on improving the second step. In this paper, we propose a differentiated back-projection (DBP)-type MAR method by employing a novel property of the DBP reconstruction algorithm described later. We expect that this method has a potential of reducing the DC-shift and the shading artifacts by suppressing the propagation of interpolation errors to a smaller neighborhood in the projection data space.

The paper is organized as follows. In Section 2, we explain the pre-processing step of projection data contaminated by the metal object by using an interpolation, and show how interpolation errors occur and propagate during the MAR reconstruction process. In Section 3, we explain how to reduce the DC-shift and the shading artifacts by reducing the propagation of interpolation errors. In Section 4, a simulation study using simulated projection data of numerical phantoms is presented. In Section 5, conclusions are described.

2. Reconstruction method for the metal artifact reduction

1) Pre-processing interpolation step in the metal artifact reduction

The 2D object to be reconstructed is denoted by \( f(\chi) \). The geometry of fan-beam CT is shown in Fig. 2(a). The X-ray source trajectory is parameterized by the variable \( \lambda \), which changes over the interval \( \Lambda \). Each source point on the trajectory is denoted by \( \bar{a}(\lambda) \). The fan-beam projection data is measured by varying the unit vector \( \bar{a} \), representing the direction of X-ray in the \( x - y \) plane, and it is expressed as

\[
g(\lambda, \bar{a}) = \int_0^{+\infty} f(\bar{a}(\lambda) + t\bar{a}) dt
\]

(1)

The vector \( \bar{a} \) is defined by \( \bar{a} = (\bar{\chi} - \bar{a}(\lambda))/\|\bar{\chi} - \bar{a}(\lambda)\| \), and \( t \) is the coordinate along each X-ray, \( i.e. \) the distance between the source point and the object point. When the X-ray passes through the metal object, the corresponding projection data is denoted by \( g_m(\lambda, \bar{a}) \). It is easy to acquire the projection data \( g_m(\lambda, \bar{a}) \) by using the re-projection and segmentation method as described in [10]. For convenience, the projection data that X-ray does not pass through the metal object is expressed as \( g_n(\lambda, \bar{a}) \). Obviously, we have
\[ g(\lambda, \alpha) = g_m(\lambda, \alpha) + g_n(\lambda, \alpha) \]  

Then, the interpolated projection data \( g_i(\lambda, \alpha) \) is expressed as

\[ g_i(\lambda, \alpha) = I(g(\lambda, \alpha) - g_m(\lambda, \alpha)) \]

where \( I \) represents an interpolation operation. Unless the interpolation method used to fill the missing projection data \( g_m(\lambda, \alpha) \) from the uncontaminated projection data \( g_n(\lambda, \alpha) \) is exact, interpolation errors will occur. In this paper, we choose the simple linear interpolation during the MAR procedure. An illustration of the interpolation step to process the metal object projection data is shown in Fig. 2(b). Hereafter, we express the interpolated projection data \( g_i(\lambda, \alpha) \) used in the reconstruction step of MAR procedure as

\[ g_i(\lambda, \alpha) = g_n(\lambda, \alpha) + g_i(\lambda, \alpha) \]

2) Analytical reconstruction algorithm after the pre-processing

The FBP algorithm is a candidate method used to reconstruct an image from the interpolated projection data \( g_i(\lambda, \alpha) \). Here, we show the improved FBP reconstruction formula discovered in [11] as following:

\[ P(\lambda, \tilde{\beta}) = \frac{1}{\tilde{\alpha}'(\lambda)} \cdot \frac{\partial}{\partial \tilde{\beta}} \int_S h_H(\tilde{\beta} \cdot \tilde{\alpha}) g_i(\lambda, \tilde{\alpha}) d\tilde{\alpha} \]

\[ f(\tilde{x}) = \frac{1}{4\pi} \int_S \int_S \frac{1}{||\tilde{x} - \tilde{\alpha}(\lambda)||} \delta(\tilde{\beta} \cdot \tilde{\alpha}) \tilde{\alpha}'(\lambda) \cdot \tilde{\beta} W(\lambda, \tilde{\beta}) P(\lambda, \tilde{\beta}) d\tilde{\beta} \int_{\tilde{\alpha}} = \frac{\tilde{x} - \tilde{\alpha}(\lambda)}{||\tilde{x} - \tilde{\alpha}(\lambda)||} \]

where \( h_H(\cdot) \) is the kernel of the Hilbert transform filter, \( \delta(\cdot) \) is the Dirac delta function, and \( S \) is the unit circle. In Eq. (5), the Hilbert filter \( h_H(\cdot) \) is employed instead of the ramp filter in the traditional FBP method, because the ramp filter can be decomposed into the succession of the Hilbert transform and the derivative. The vector \( \tilde{\alpha} \) is directed from the source point \( \tilde{\alpha}(\lambda) \) to the object point \( \tilde{x} \), and is orthogonal to the unit vector \( \tilde{\beta} \). The vector tangent to the trajectory at \( \tilde{\alpha}(\lambda) \) is expressed as \( \tilde{\alpha}'(\lambda) = \partial \tilde{\alpha}(\lambda) / \partial \lambda \). It is known that, when the trajectory is convex and is smooth, \( \tilde{\alpha}'(\lambda) \) always exists and is non-zero. The weighting function \( W(\lambda, \tilde{\beta}) \) is used to normalize the redundancy of projection data. Note that the computation of non-local Hilbert filter is located before the back-projection step. This means that, in each projection view \( \lambda \), the interpolation errors contained in the projection data \( g_i(\lambda, \alpha) \) is spread over the whole uncontaminated projection data \( g_n(\lambda, \alpha) \), as a result, the interpolation errors exist everywhere in the projection data \( g_i(\lambda, \alpha) \). We illustrate an example in Fig. 3(a).

Note that, in the FBP method, the Hilbert filtered projection data contains the interpolation errors over the whole projection space, which is used in the back-projection step. Finally, the reconstructed image is obtained, but the

Fig. 2 (a) The geometry of fan-beam CT for the object containing an metal object, and (b) the interpolation process to fill the metal contaminated part of projection data.
interpolation errors are strongly spread over the whole object space leading to the DC-shift and the shading artifacts.

Recently, a two-step analytical DBP reconstruction algorithm was proposed [12]. It was mainly developed to reduce artifacts caused by the truncation of projection data. The DBP algorithm has a novel feature to solve the exterior and interior truncation problems. Here, we show the reformulated DBP reconstruction formula for the MAR as

$$P(\lambda, \tilde{\beta}) = \frac{1}{\tilde{a}'(\lambda)} \frac{\partial}{\partial \lambda} \int_S \delta(\tilde{\beta} \cdot \tilde{a}) g_i(\lambda, \tilde{a}) d\tilde{a} \tag{7}$$

$$f_{\tilde{\beta}}(\tilde{x}) = \frac{1}{4\pi} \int_{\lambda} \int_S \frac{1}{\|\tilde{x} - \tilde{a}(\lambda)\|} \delta(\tilde{\beta} \cdot \tilde{a}) |\tilde{a}'(\lambda) \cdot \tilde{\beta}|$$

$$\text{sgn}(\tilde{\beta} \cdot \tilde{\beta}) W(\lambda, \tilde{\beta}) P(\lambda, \tilde{\beta}) d\tilde{\beta} \bigg|_{\tilde{a} = \frac{\tilde{x} - \tilde{a}(\lambda)}{\|\tilde{x} - \tilde{a}(\lambda)\|}} \frac{d\lambda}{\|\tilde{x} - \tilde{a}(\lambda)\|} \tag{8}$$

where $\tilde{\beta}$ is the unit vector that determines the direction of Hilbert filter applied after the back-projection. The main difference between the DBP and FBP algorithms is the location of non-local filtering operation, where it is located after the back-projection step in the DBP method. Therefore, as shown in Fig. 3(b), unlike the FBP method, the DBP method allows to use not only the projection data contaminated by the metal object $g_i(\lambda, \tilde{a})$ containing the interpolation errors but also the correct data corresponding to the non-metal object $g_0(\lambda, \tilde{a})$. Finally, the non-local Hilbert filter operation can be applied after the back-projection step along a preferred Hilbert filter direction [12].

As mentioned above, although the DBP reconstructed image $f_{\tilde{\beta}}(\tilde{x})$ in Eq. (8) is still not an exact reconstruction, the existence of back-projected data which is free from the interpolation errors in the DBP algorithm gives an intuitive expectation to improve image quality in the MAR method. It is likely that its success depends on the choice of a proper Hilbert filter direction in the final Hilbert filtering step. The general rule in choosing the best direction of Hilbert filter would be the one such that the propagation of interpolation errors during the computation of Hilbert filter can be avoided as much as possible. We show some examples of the best direction in Fig. 4. Theoretically, in both the FBP and DBP algorithms, it cannot be avoided for the incorrect projection data to spread over the whole space. However, thanks to the local feature of the DBP algorithm, the level of spreading out in the DBP seems to be clearly smaller compared to the FBP. We also note that image quality for projection data of non-metal object by the DBP algorithm is almost same as that by the FBP algorithm, because they have the similar analytical structure.
Fig. 4 Examples of the proper direction of Hilbert filter in different geometries of the metal object. The dark ellipse represents the metal object inside the whole object. The arrow represents the proper direction of Hilbert filter in each case. Correspondingly, in the bottom row, the rectangle represents the area including a large effect of interpolation errors in the reconstructed image. Outside the rectangle, it is expected that the artifacts by the DBP algorithm is smaller than those by the FBP algorithm.

3. Simulation study

A simulation study was performed using numerical phantoms (long-object phantom and Shepp-Logan phantom) containing a metal object. We designed the long-object phantoms as a particular example such that the use of projection data passing through the metal object can be avoided as much as possible when using the DBP algorithm. The definitions of long-object phantom is given in Table 1, and the phantom is shown in Fig. 5(a). With respect to the fan-beam geometry, the standard circular X-ray source trajectory and the collinear detector array were assumed. The radius of circular orbit was 8 (cm), the reconstructed image consisted of 512 × 512 (pixels), and the pixel size was 0.004 (cm). The detector array consisted of 512 (channels), and the width of channel was 0.004 (cm). The number of projection data was 1024 over, 360° from which the weighting function $\Phi(\lambda, \beta)$ in Eq. (8) was 0.5. For the DBP-type MAR method, the direction of Hilbert filter $\theta$ was horizontal ($\theta = 0$) which seems to be the proper one from Fig.4.

We show the simulation results for the long-object phantom in Fig. 5. As shown in Fig. 5(g-i), after subtracting the metal object projection data $g_m(\lambda, \alpha)$ from the original projection data $g(\lambda, \alpha)$ by the re-projection and segmentation method [10], the linear interpolation was applied to complete the missing part of projection data. The metal contaminated region of original projection data was identified using the thresholding operation with a manually chosen constant threshold [10]. The original phantom and reconstructed images by the FBP-type and DBP-type MAR methods are shown in Fig. 5(a-c), the corresponding profiles are shown in Fig. 5(d-f). It observed that the top part of object containing small structures in Fig. 5(b) are invisible due to the DC-shift and the shading artifacts, however, in Fig. 5(c), we can clearly observe those small structures. With no apparent loss in spatial resolution and image contrast, the proposed method reduced the DC-shift and the shading artifacts, especially, in the region that is not directly adjacent to the metal object. To observe the improvement in image quality, we compared profiles along

<table>
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<th>Ellipsoid</th>
<th>Center</th>
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<th>Minor Axis</th>
<th>Rotation Angle</th>
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<tr>
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<td>0.04</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>(0.6,0.08)</td>
<td>0.04</td>
<td>0.04</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>5</td>
<td>(0.5,−0.08)</td>
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<td>0.04</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>6</td>
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<td>0.05</td>
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</tr>
<tr>
<td>7</td>
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<td>0.06</td>
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a vertical line $x = 256, y \in [30, 130]$, which is directed from the upper part to the metal object. It is noticed that the profile of DBP reconstruction (Fig. 5(f)) is closer to that of the phantom (Fig. 5(d)) compared to the FBP reconstruction (Fig. 5(e)).

We also tested the proposed method by using the Shepp-Logan phantom. Fig. 6 shows the reconstruction images. Note that the corresponding reconstructed images without the MAR is shown in Fig. 1(b). It is observed that both the FBP-type and DBP-type MAR methods are successful to reduce the metal artifacts. In other words, the Sheep-Logan phantom was not the case, in which the local property of DBP-type MAR method helps in further improving image quality compared to the FBP-type MAR method. Fig. 7 shows the reconstruction results when Poisson noise was added to the projection data. It can be observed that improvement in image quality achieved by the DBP-type MAR method is comparable to the case of ideal projection data without noise. This result indicates stability of the proposed method against statistical noise.

4. Conclusions

Using the recently developed DBP reconstruction algorithm [12], this paper proposed a method to reduce the effect of interpolation errors in the metal artifact reduction (MAR) based on filling the metal contaminated part of y

Fig. 5 Reconstructed images of the long-object phantom. (a) The long-object phantom; (b) the reconstructed image from projection (i) by using the FBP-type MAR method; (c) the reconstructed image from projection (i) by using the DBP-type MAR method; (d), (e), (f) are the profiles corresponding to (a), (b), (c) along the vertical line $x = 256, y \in [30,130]$ respectively; (g) the original projection data; (h) the metal object subtracted projection data; (i) the interpolated projection data. The display gray scale for (a), (b), (c) is [0.55,1.35]. The display gray scale for (g), (h), (i) is [0.0, 1.28].
projection data by an interpolation. The performance of the proposed method was tested with a long-object phantom and the Shepp-Logan phantom. In the traditional MAR methods, the metal artifacts are reduced by replacing the metal contaminated part of projection data by a smooth function obtained from an interpolation. This simple approach leads to reducing streak artifacts in the reconstructed image. However, the interpolation errors occurred in the interpolation step introduces the DC-shift and the shading artifacts in the reconstructed image. The aim of this work was to reduce such low-frequency artifacts. The key idea of proposed DBP-type MAR method was to utilize the novel local feature of DBP algorithm, which has a potential to suppress the propagation of interpolation errors coming from the metal contaminated part of projection data to the whole projection data. As a result, in the simulation study using a long-object phantom, there was a visible improvement in reducing the DC-shift and the shading artifacts compared to the standard FBP-type MAR method.

During the simulation study, however, we found that the degree of image improvement achieved by the proposed DBP-type MAR method strongly depends on the object and the imaging situation. For example, as shown in Fig. 6, the proposed method was not effective for the Shepp-Logan phantom, because the width of the metal object dose not expand to the border of whole object. Characterizing the cases where the proposed method is effective is a future work to be investigated.

References


補間誤差低減による X 線 CT のための改良型メタルアーティファクト削減手法

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本論文では、X 線 CT におけるメタルアーティファクト問題を取り扱う。CT において X 線を通さない金属物体が被写体内部に存在する場合、再構成画像に筋状アーティファクトが発生して画質を低下させる。この問題を回避する簡便な解析的画像再構成法として、金属を通過する値が大きい投影データを周囲の投影データから補間により埋め、その後にフィルタ補正逆投影（FBP）法により画像再構成を行う手法が用いられる。しかし、この手法では、補間誤差が画像再構成の過程でランプフィルタ処理と逆投影により画像全体に大きく伝播して、直流シフトやシェーディングアーティファクトが発生する。本論文では、補間誤差の影響を削減する手法として、FBP 法の代わりに微分逆投影（DBP）法を適用することに基づく新手法を提案する。DBP 法では、フィルタ処理と逆投影の順序を逆転させフィルタ処理を逆投影後にユーザが選択した方向に行えるため、金属部分の投影データの補間誤差が広がる効果を抑制することが可能で、これによりアーティファクトを削減する効果が期待される。提案手法の有効性をシミュレーション実験により示す。

キーワード：X 線 CT，画像再構成，メタルアーティファクト，補間誤差

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