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Image-based Metal Artifact Reduction in X-ray Computed Tomography utilizing Local Anatomical Similarity

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Abstract

X-ray computed tomography (CT) is widely used in radiation therapy treatment planning in recent years. However, metal implants such as dental fillings and hip prostheses can cause severe bright and dark streaking artifacts in reconstructed CT images. These artifacts decrease image contrast and degrade HU accuracy, leading to inaccuracies in target delineation and dose calculation. In this work, a metal artifact reduction method is proposed based on the intrinsic anatomical similarity between neighboring CT slices. Neighboring CT slices from the same patient exhibit similar anatomical features. Exploiting this anatomical similarity, a gamma map is calculated as a weighted summation of relative HU error and distance error for each pixel in an artifact-corrupted CT image relative to a neighboring, artifact-free image. The minimum value in the gamma map for each pixel is used to identify an appropriate pixel from the artifact-free CT slice to replace the corresponding artifact-corrupted pixel. With the proposed method, the mean CT HU error was reduced from 360 HU and 460 HU to 24 HU and 34 HU on head and pelvis CT images, respectively. Dose calculation accuracy also improved, as the dose difference was reduced from greater than 20% to less than 4%. Using 3%/3mm criteria, the gamma analysis failure rate was reduced from 23.25% to 0.02%. An image-based metal artifact reduction method is proposed that replaces corrupted image pixels with pixels from neighboring CT slices free of metal artifacts. This method is shown to be capable of suppressing streaking artifacts, thereby improving HU and dose calculation accuracy.

Keywords

Metal artifact reduction; anatomical similarity; CT; dose accuracy

1. INTRODUCTION

X-ray computed tomography (CT) is widely used in radiotherapy treatment planning for target delineation and dose calculation. Unfortunately, metal implants, such as dental fillings and hip prostheses, cause severe bright and dark streaking artifacts in reconstructed CT images. It has been reported that approximately 10% of CT images involve extracranial metal artifacts[1]. These streaking artifacts decrease image contrast and degrade HU accuracy, leading to inaccuracies in target delineation and dose calculation [2-7].

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The leading cause of these artifacts is photon starvation along the projection paths that pass through metallic object. X-rays are highly attenuated by metallic inserts, resulting in insufficient photons available for measurement of projection. The incomplete projections introduce streaking artifacts in the CT image with filtered back projection (FBP) reconstruction method[4]. Various approaches have been proposed to alleviate or correct for metal artifacts. Many of the metal artifact reduction (MAR) methods compensate for missing projection data to suppress the streaking artifacts in the reconstructed image. The corrupted projection data are replaced with either interpolation methods or iterative reconstruction methods [8-12]. Megavoltage projection data can also be used to patch the corrupted pixels in kV projections [13]. Due to the relatively low absorption of metal object, MV x-rays are less affected by photon starvation and provide more accurate measurement of attenuation coefficients. These methods have achieved varying degrees of success, with the performance of the methods depending on the accuracy of the underlying estimation models.

While the majority to MAR methods were performed in the sinogram domain, image-based approaches have also shown merit. Park *et al.* made use of MRI images to map metal artifact corrupted CT pixels with pixels from a neighboring, artifact-free slice[14]. This method improves CT image quality and proton range calculation accuracy, but requires prior MR images for pixel mapping. The method is therefore applied primarily on cranial images.

In this work, an image-based method for metal artifact reduction is presented which exploits the anatomical similarity between neighboring CT slices without the availability of a complementary MR image set.

2. METHOD

Rather than compensating for the metal artifact corrupted pixels in the sinogram domain, the proposed method performs correction directly on reconstructed images. In particular, adjacent CT slices of the same patient often show anatomical similarity. Figure 1 presents three neighboring CT image slices for a head-and-neck patient. While the images suffer from different severities of metal artifacts, great anatomical similarity between the slices can be observed. Utilizing this anatomical similarity, the corrupted pixels are replaced with corresponding pixels from artifact-free images. To find the corresponding pixels, a gamma map was first calculated, which is a weighted summation of relative attenuation coefficient error and the distance error, as shown in Eqn [1].

$$\gamma_{i,j} = \left| \frac{\mu_{i,j}^{ma} - \mu_{i',j'}^r}{\mu_{i',j'}^r} \right|^2 + w \left| \frac{\vec{r}_{i,j}^{ma}}{r_{i',j'}^r}, \frac{\vec{r}_{i',j'}^r}{r_{i',j'}^r} \right|^2 \quad (1)$$

where $\mu_{(i,j)}^{ma}$ and $\mu_{(i',j')}^r$ are the linear attenuation coefficients associated with the (i, j) pixel of the artifact-corrupted and the (i', j') pixel of the artifact-free reference images. $\left| \frac{\vec{r}_{i,j}^{ma}}{r_{i',j'}^r}, \frac{\vec{r}_{i',j'}^r}{r_{i',j'}^r} \right|$ is the 2D distance between these pixels, and w is a weighting factor, which is $\sim 10^{-3}$ in this study. A threshold value is empirically chosen to select artifact-corrupted

pixels. If the minimum value of the gamma map for the (i, j) pixel of the artifact-corrupted image is less than the threshold, that pixel is considered as artifact-free and remains unchanged. However, if the minimum gamma value is larger than the threshold, the corrupted pixel in question is replaced by the pixel from the artifact-free image yielding the minimum gamma value. In this study, the threshold was chosen empirically to be $\sim 10^{-1}$.

To evaluate the performance of the proposed method on streaking artifact and HU error correction, we first apply the image-based metal artifact reduction method on patient head images with dental fillings. We also simulated hip implants on one set of pelvic patient data without metal artifacts to evaluate the performance the proposed method on dose estimation accuracy. Metal artifacts are obtained by forward projection and then reconstruction on the CT images with simulated metallic implants. The dose distributions were calculated with two lateral $10 \times 10 \text{ cm}^2$ fields. Each beam was set to 98 MU, which results in 100 cGy to isocenter on the reference CT images with simulated metallic implants. The simulated metallic inserts results in more than 400 HU error, and over 10% dose calculation error in the metal artifact corrupted CT image, which matches what were found in previous study[15].

3. RESULTS

Figure 2 shows two CT images for a patient with dental fillings. Prior to correction, the highly attenuating dental fillings result in substantial streaking, and the HU accuracy and the image contrast are degraded. As shown on the right side of the figure, the presented image-based MAR approach suppresses the streaking and improves the delineation of the dental fillings. In particular, the HU error was reduced from 360 HU to 24 HU in the uniform area adjacent to the fillings. Similar results were observed on patient images with simulated hip implants. As shown in Figure 3, the proposed method substantially suppresses streaking, and the CT number error in the central area is reduced from 460 HU to 34 HU. Metal artifact correction is particularly important for pelvis patients since hip prostheses are generally larger than dental fillings and the resulting streaking artifacts affect a greater tissue volume.

Figure 4 shows the dose distribution for the reference pelvis CT image with simulated hip implants. The dose is calculated with two lateral beams. Since the dose distribution is sensitive to body boundary, the surface was not considered in the dose comparison. Only the dose distribution in the central region, indicated by the dashed square in the figure, was considered. Figure 5 shows the dose difference with and without the proposed metal artifact reduction method applied. The HU inaccuracy resulting from the hip implant artifacts causes errors in the dose estimation ranging from -13.7% to 25.7% . This result is consistent with Monte-Carlo calculations reported in the literature [15]. The proposed method eliminates the streaking artifacts and improves image accuracy. With improved HU accuracy, the dose error is reduced, ranging from -3.7% to 3.9% .

Gamma analysis is one of the most widely used dose comparison methods, indicating how close two dose distributions are by taking both dose difference and distance difference into consideration. Figure 6 shows the gamma analysis results with 3%/3mm criteria. Without any correction, 23.25% of dose points failed the gamma analysis. After metal artifact

reduction, only 0.02% of dose points failed the 3%/3mm gamma criteria. The dose improvement can also be observed in Figure 7, which shows the sagittal and coronal dose profiles as indicated by the two dashed lines in Figure 4. With the proposed method, the dose profiles are greatly enhanced and match the reference profiles better.

4. CONCLUSIONS

An image-based metal artifact reduction method was presented that replaces corrupted image pixels with pixels from neighboring slices free of metal artifacts. This method was shown to be capable of suppressing streaking artifacts, thereby improving both HU and dose calculation accuracy.

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Figure 1. Three adjacent CT slices from a head and neck patient. Though suffered from different severities of metal artifacts, the three images show great anatomical similarity.

Figure 2.

Left: CT image with metal artifacts arising from dental fillings. Right: CT image with the proposed metal artifact reduction method. The CT number error was reduced from 360 HU to 24 HU in the artifact-corrupted area indicated by the dashed square in the left figure.

Figure 3.

Left: CT image with metal artifacts arising from simulated hip implants. Right: CT image with the proposed metal artifact reduction method. The CT number error was reduced from 460 HU to 34 HU in the central area indicated by the dashed square in the left figure.

Figure 4. Dose distribution on the reference image with simulated hip implants. To exclude the effect of body boundary on dose calculation, we only compared dose distribution inside the dashed square.

Figure 5.

Left: Dose difference calculated on CT images with metal artifacts. Right: Dose difference on CT images utilizing the proposed metal artifact reduction method.

Figure 6. Left: Gamma analysis results without correction. Right: Gamma analysis results with the proposed metal artifact reduction method. The red dots indicate pixels failing 3%/3mm criteria.

Figure 7.

The comparison of sagittal (left) and coronal (right) dose profiles as indicated by the two dashed lines in Figure 4.