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| 氏名 | 加納　徹 |
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Novel reconstruction algorithms for metal artifact reduction in X-ray CT imaging
（X 線 CT 画像におけるメタルアーチファクト低減のための新しい再構成アルゴリズム）

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| 論文審査委員 | 主査　准教授　小関 道彦 |
| | 教　授　小林 俊一 |
| | 准教授　河村 隆 |
| | 准教授　Todd Colin Pataky |
| | 教　授　伊能 教夫　（東京工業大学） |

# 論　文　内　容　の　要　旨

X-ray computed tomography (X-ray CT) is an established imaging technology used for non-invasive diagnoses and inspections. Cross-sectional images are reconstructed from projections of multi-directional beam data. Although X-ray CT brought a lot of benefit to us, many technical challenges remain. In particular, metal artifacts are a significant problem in CT imaging. A metal artifact is a strong radial noise caused by a discrepancy of projection data, and makes it difficult to diagnose and inspect with metal objects. In this study, we propose novel reconstruction algorithms to reduce metal artifacts, and to establish more accurate inspectional techniques.

First, physics and principles of X-ray CT were introduced, and the causes of metal artifacts were clarified. Then X-ray simulation software was developed on the basis of physical backgrounds. From the simulation experiments that assumes actual projection conditions, it was found that metal artifacts could be generated on simulations. Validity of our forward projection and back projection calculations were verified by comparing actual CT data to simulation data. Also, the new quantitative evaluation method SLP, which is based on two-dimensional Fourier transform, was established by using the simulation technology.

As a novel algorithm, the metal artifact reduction method based on a nature of a sinogram was proposed. A sinogram consists of the aligned projection data in a specific X-ray cross section. Since forward projection is performed while the X-ray source (or an object) rotates around a specific axis, the sinogram is composed of various sine curves of period $2\pi$ for each object/feature. By tracing out sine curves on sinograms, many information can be extracted. Our idea is to use the sine curve information, and to reconstruct the separate metal and non-metal cross-sectional images. As a result of application to actual CT data and simulation data, metal artifacts were effectively reduced in both cases, but peripheral regions of metals tended to become blurred. In the simulation experiments, we gradually changed the amount of metal on the numerical phantoms, in order to verify the performance limit of our algorithm. Then it was confirmed that the performance of metal artifact reduction decreased with increased amount of metal on cross-section. However, since this algorithm requires little time and

obtain enough images for diagnoses and inspection in most cases, it is thought that our algorithm is useful.

Another novel metal artifact reduction method based on iterative reconstruction was proposed to solve the problem remained in the previous method. We first introduced the formula for deriving X-ray attenuation coefficient distributions. Then, by incorporating forward projection calculations that include energy information to iterative reconstruction, a new theory of metal artifact reduction was established. When the $X$-$Y$ coordinate system is defined by rotating the $x$-$y$ coordinate system $\theta$ degrees, the proposed equation of iterative calculations is expressed as:

$$\mu(x,y,E)^{(k+1)} = \mu(x,y,E)^{(k)} + \left\{ p(X,\theta_k) + \ln \frac{\int_E I_{\rm in}(X,\theta_k,E)\exp\left(-\int_{-\infty}^{\infty}\mu(x,y,E)^{(k)}dY\right)EdE}{\int_E I_{\rm in}(X,\theta_k,E)EdE} \right\} d\theta,$$

where $\mu$ is the X-ray attenuation coefficient, $E$ is the X-ray energy, $I_{\rm in}$ is the incident X-ray intensity and $k$ is the iterative number. Since the idea is different from interpolations or improvements for projection data, it could reduce metal artifacts primordially. We applied our algorithm to actual CT data, thereby advantages over the technique proposed in the method based on sine curves were shown. In the application to actual data, extracted metal regions were needed as initial images in iterative reconstruction to accelerate the convergence of images and to prevent from the divergence. On the other hand, since the projection conditions are completely represented by numerical values in simulation experiments, images will not diverge and initial images of metal regions are not necessary. As a result of application to simulation data, precise metal shapes were extracted, and metal artifacts were dramatically reduced. This result implies that actual data also can be significantly reduced by improvements of projection calculations. Besides, our method based on iterative reconstruction requires more calculation time than the method based on sine curves. However, this is problem is also possible to be solved by using GPGPU.

These proposed metal artifact reduction methods were targeted at a two-dimensional image. Therefore, our algorithms were extended to three-dimensional one so as to widely disseminate our superior technology. We first introduced the concept of a fan beam reconstruction algorithm without fan/parallel conversion. Next, we derived a cone beam reconstruction algorithm and projection calculations by extending the fan beam one. Once the three-dimensional forward projection and back projection formulated, our metal artifact reduction algorithms can be applied to cone beam data. Then the theories of three-dimensional metal artifact reductions were established. Validation was performed using a physical phantom and a three-dimensional numerical phantom, and the availability for cone beam data was demonstrated. At the same time, it was found that it is difficult to apply the algorithm to some regions for three-dimensional data.

In this thesis, although it was succeeded to significantly reduce metal artifacts, some technical challenges remain. In the future, it is planned to consider the improvements of our algorithms. In addition, we will cooperate with hospitals and companies that are troubled by metal artifacts, and expand the application range.