The Johns Hopkins University
Advanced Computer Integrated Surgery

Group 4
Metal Artifact Removal in C-arm Cone-Beam CT

Paper Seminar Critical Review of

"Frequency split metal artifact reduction (FSMAR) in computed tomography"

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Published in The International Journal of Medical Physics Research, April 2012.

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CIS II Project Background

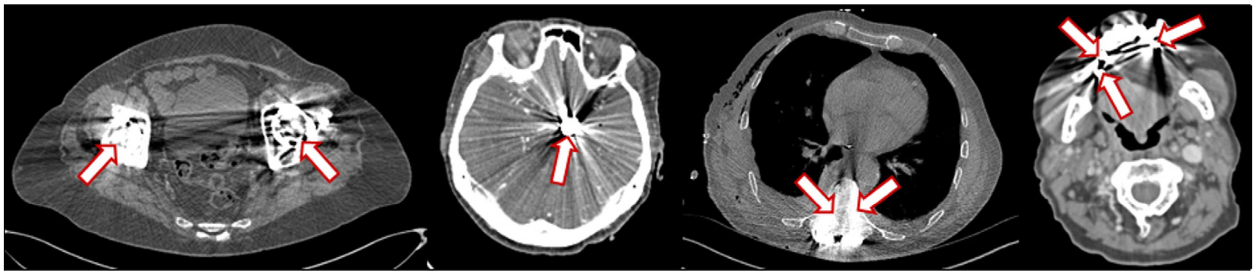
A number of prevalent pathologies presenting a major disease burden, including arterial aneurysms, stenosis, and AVMs, may be treated with a variety of interventional techniques, including clips, coiling, stenting, and other measures. Such interventions are often performed with spatial localization and guidance provided by X-ray CT imaging methods available in the interventional suite. However, the interventions often utilize devices consisting of dense material (metal) that can result in artifacts that degrade CT image quality due to effects such as "photon starvation" and "beam hardening." Such artifacts can challenge the visibility of structures of interest and reduce the precision and effectiveness of the intervention. As such, the development of effective metal artifact correction techniques is necessary; many MAR methods have been developed and are ready for clinical testing. Prior to clinical trials with such MAR techniques, quantitative analysis of their performance is essential. Our project, "Metal Artifact Removal in C-arm Cone-Beam CT," undertakes such quantitative assessment by testing a recently developed MAR technique in neurovascular interventions (e.g., treatment of aneurysms with surgical clips and coils) guided by tomographic x-ray imaging (e.g., cone-beam CT on a Zeego C-arm) using custom phantoms designed to emulate pertinent clinical scenarios and provide quantitative analysis of image quality and accuracy.

Paper Selection

The paper I have chosen for critical review is "Frequency split metal artifact reduction (FSMAR) in computed tomography" by Meyer et al., published in *The International Journal of Medical Physics Research* in April of 2012. This paper aims to present a new MAR technique, frequency split metal artifact reduction (FSMAR), that ensures efficient reduction of metal artifacts at high image quality with enhanced preservation of details close to metal implants. With regards to our own project, this paper is highly relevant as it explicitly outlines the implementation of the FSMAR method and compares the effectiveness of various combinations of MAR method options. In our project, we hope to assess the MAR algorithm available on the Siemens workstation; it could prove useful to compare the artifact reduction of the Siemens implemented MAR method to the FSMAR and other MAR techniques as a way of specifically quantifying artifact reduction.

Summary of Problems

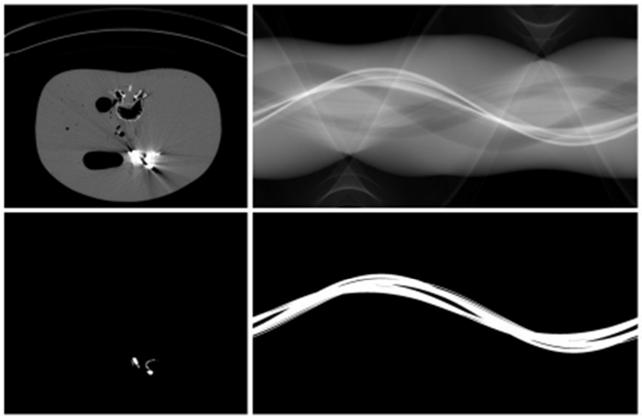
Metal implants create severe artifacts that degrade image quality and reduce the diagnostic value of CT images. Standard MAR techniques are far from perfect: sinogram inpainting-based MAR methods simply remove data of the metal implants which leads to blurring and loss of critical information. Inpainting-based methods for MAR consider those parts of the projection data that are affected by metal as completely unreliable. This assumption that the data from the metal trace are useless is only valid for very thick and dense implants where photon starvation occurs. The region close to metal implants is often not well corrected when inpainting-based MAR methods are used.



Examples of CT images with metal artifacts. The arrows indicate the position of the metal implants. From left to right, a patient with bilateral hip prosthesis, one with neurocoil, with spine fixation, and with dental fillings is shown. Image provided by Meyer et al.

Technical Background

Metal artifacts represent the extremes of the beam hardening phenomenon since the complete attenuation of the beam results in gaps on the data from these shadows in the projection data. When using a filtered-backprojection method, these gaps in the projection data produce dark bands on the images around the metallic object. Sinogram inpainting methods are the most common MAR technique employed to correct such metal artifacts. These methods utilize interpolation or forward projections to complete the sinogram, where metal-affected values are treated as missing data. The first step to reduce the existing metal artifacts consists of a segmentation of the metal trace. Metal objects are labeled in a preliminary filtered backprojection reconstruction through the use of a simple threshold segmentation. Then, a forward projection of the metal-only image is calculated resulting in a sinogram mask. All sinogram values that are different from zero in this mask are assumed to be inconsistent. Next, the inconsistent data is replaced through a two-dimensional sinogram restoration technique. The gap inside the sinogram data, the inpainting region, is filled in such a way that it is not detectable in the resulting image. After a number of iterations of inpainting, the repaired sinogram data are reconstructed. However, this method tends to introduce new streak artifacts during sinogram restoration. The origin of these new artifacts is related to the loss of edge information of the objects by using surrogate data. This loss of edge information affects the entire image and is not restricted to edges next to metal objects.



Upper row: The original sinogram data and the corresponding reconstruction of the body phantom. Bottom row: The binary mask which depicts the distribution of the dense implants. Additionally the binary forward projection of this mask is shown. Image provided by Mueller et al.

FSMAR Algorithm

As depicted in the schematic diagram, the FSMAR algorithm consists of five steps, as outlined below.

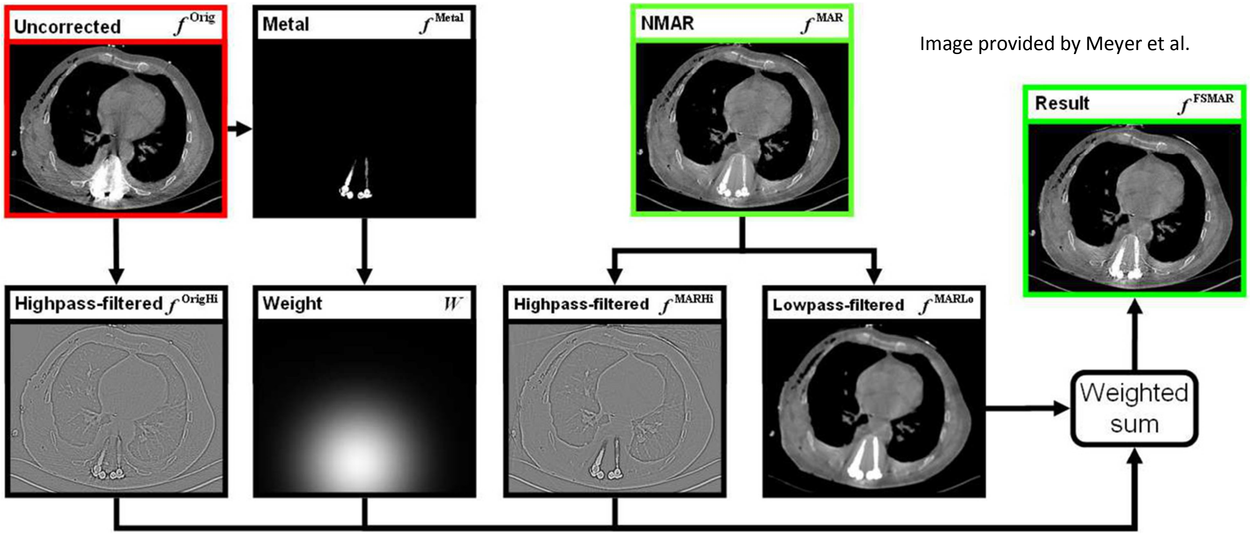


Image provided by Meyer et al.

1) Preprocessing
    - An adaptive filter is applied to the raw data to reduce noise. For standard inpainting-based MAR approaches, this is unnecessary because the noisiest data, the data from the metal shadow, are completely replaced. For FSMAR, the data from the metal shadow contribute to the final image and thus, noise reduction is recommended. From this preprocessed raw data, an image f^{Orig} is reconstructed.
2) Segmentation of metal
    - From the image f^{Orig}, a metal image f^{Metal} is segmented by simple thresholding. This image contains only data for metal implants; any pixels that are not metal are set to zero. The threshold was chosen as a fixed percentage of the maximal CT value found in f^{Orig}.
3) MAR by sinogram inpainting
    - An image corrected by an inpainting-based MAR method is computed and designated as f^{MAR}. The metal image, f^{Metal} is forward projected and the locations of the positive entries from this projection dataset define the metal trace to be replaced by the inpainting method. Any MAR inpainting method can be employed here; the method of choice in this paper is normalized metal artifact reduction (NMAR).
4) Frequency Split
    - FSMAR combines parts of the high frequencies of the image f^{Orig} with image f^{MAR}. The low-pass filtered images are computed by a 2D-convolution with a Gaussian G(σ) as $f^{OrigLo} = f^{Orig} * G(\sigma)$ and $f^{MARLo} = f^{MAR} * G(\sigma)$. The high frequencies of the images are obtained by subtracting the low-pass filtered versions: $f^{OrigHi} = f^{Orig} - f^{OrigLo}$ and $f^{MARHi} = f^{MAR} - f^{MARLo}$. f^{MAR} is more reliable than f^{Orig} with respect to low frequencies as it does not contain beam hardening and scatter artifacts due to metal. f^{OrigHi} contains the edges and fine anatomical structures as well as some remaining streak artifacts due to noise. f^{MARHi} contains less noise, but also contains less edge details of anatomical structures close to the metal implants. Thus, a spatially varying weight is used to combine the advantages of both high-frequency images.
5) Spatial Weighting
    - Pixels close to the metal implants are weighted higher than pixels more distant to the implants. The final FSMAR-corrected image f^{FSMAR} is the weighted sum $f_{ij}^{FSMAR} = f_{ij}^{MARLo} + W_{ij} f_{ij}^{OrigHi} + (1 - W_{ij}) f_{ij}^{MARHi}$, with i = 1,…,I and j = 1,…,J, where I is the number of rows and J the number of columns in an image.

Results

FSMAR was tested on two body phantoms and five patients with varying metal implants. For comparison, all datasets were corrected with a standard sinogram inpainting method, MAR1, and NMAR, and both with and without frequency split. Phantom images were taken with and without metal artifacts and quantitatively compared using RMSE calculations. Patient results were purely qualitative. Specific details are as follows:

- Hip phantom with bilateral hip prosthesis: in the region of interest surrounding the metal artifacts, the combination of MAR1 and FSMAR performs better than MAR1 alone. The combination of NMAR and FSMAR yields the lowest RMSE and can thus be considered the best performance. The FSMAR clearly restores missing data of the fine details of anatomical structures close to the metal artifacts.
- Patient with bilateral hip prosthesis: the uncorrected image shows dark and bright artifacts. In the MAR1 result, those artifacts are removed, but between the two prostheses and tangent to the prosthesis, some new artifacts appear. The correction with NMAR is already quite satisfactory, but parts of the bone close to the implant are blurred or disappear. In the FSNMAR result, the bone is clearly visible and has a sharp contour everywhere.
- Patient with unilateral hip endoprosthesis: dark artifacts emerging from the metal and from the guts are visible in the MAR1 images with and without frequency split. Several of the thinner parts of the hip bone can only be seen in the images with frequency split. FSMAR with NMAR yields the best correction.

- Patient with internal spine fixation: as large parts of raw data are replaced and the implants have not a round but an elongated shape, the MAR1 and the NMAR results are relatively blurry in the closest vicinity of the screws. With the frequency split, the outline of the vertebra can be recovered. Even between the screws, there are bone structures visible, which are obscured by artifacts in the original image.
- Patient with dental fillings: in the MAR1 and NMAR images without frequency split, the reinserted metal implants are too small. Additionally, the edges appear artificially sharp. Using the frequency split method, the true outlines of the smaller implants are restored as the outline does not depend on the metal threshold here. However, this is an example where some details are removed by all MAR methods. Also, some parts of the artifacts are sharp enough here to be reintroduced by the frequency split.
- Patient after coiling of an intracranial aneurysm: the uncorrected image exhibits strong dark and bright streak artifacts, which make the region around the coil almost useless. The artifacts are removed by both MAR1 and NMAR, even if MAR1 introduces new artifacts. Close to the coil, a white ring-shaped artifact and slight blurring are visible after MAR1 and NMAR. In the frequency split versions, some slight streaks are reintroduced, but the blurring is removed.

Benefits and Limitations of FSMAR

FSMAR has several advantages compared to other MAR methods. In the corrected images, clear edges and fine anatomical details are recovered. As demonstrated, FSMAR can even restore structures between or within metal implants under the condition that they are sharp enough. The images exhibit a natural noise structure and no artificial image impression is created. The outline of metal implants is more accurate than after applying MAR methods that use segmentation by simple thresholding of metal but do not use edge information. In addition to a correction with an inpainting-based MAR method, FSMAR requires only the image-based filtering, multiplication, and addition of three volumes. Thus, compared to iterative methods or methods with complex inpainting schemes, the algorithm is computationally very efficient. However, in order to prove the success of FSNMAR, a more objective and extensive clinical evaluation by medical experts will be necessary.

My Assessment

In most cases, FSMAR does appear to produce superior results to any sinogram inpainting-based MAR method alone. Fine anatomical details and edges are obviously much more visible in most of the presented cases. However, personally, I am unconvinced by the figures presented specifically for the patient after coiling of an intracranial aneurysm. The ring-shaped artifact is removed with the FSMAR technique, but it does not appear to me that the blurring is removed with FSMAR. FSMAR seems to be more effective for large metal implants such as spine screws as opposed to small metal coils, but further clinical testing is required to be conclusive. In addition, Meyer et al. employed the same thresholding and Gaussian filtration parameters to every patient; it is necessary to test whether FSMAR could be improved even further with variable parameter sets. Finally, while the qualitative assessments of patient data is fairly convincing as to the effectiveness of FSMAR, it would be preferable to see any sort of quantitative calculation of the degree of artifact reduction in the various MAR methods. Hopefully, our project will make significant progress with regards to this final point in developing a quantitative measurement of streaking artifacts.