The Johns Hopkins University
Advanced Computer Integrated Surgery

Group 4

Metal Artifact Removal in C-arm Cone-Beam CT

Paper Seminar on

"Normalized metal artifact reduction (NMAR) in computed tomography"

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CIS II Course Project Background

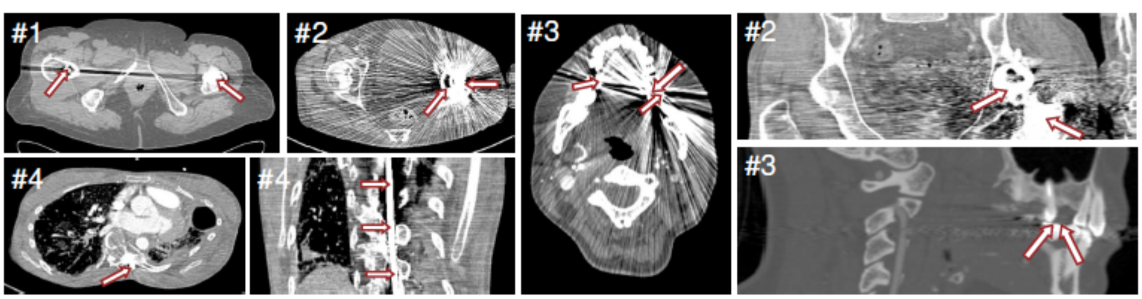
Current endovascular interventional techniques for treatments of arterial aneurysms, stenosis and arteriovenous malformations (AVMs) are often performed with image guidance provided by x-ray computed tomography (CT). However, these endovascular interventions utilize devices consisting of dense metal objects that produce metal artifacts in the acquired CT image, seriously degrading its image quality. Metal artifact removal (MAR) algorithms have been developed to reduce the image degradation and are ready for clinical testing. Our project, 'Metal Artifact Removal in C-arm Cone-Beam CT', undertakes quantitative assessments by testing a recently developed MAR technique in neurovascular interventions (i.e., treatment of aneurysms with surgical clips and coils) guided by tomographic x-ray imaging (i.e., C-arm cone-beam CT) using custom phantoms designed to emulate relevant clinical scenarios and provide quantitative analysis of image quality and MAR algorithm accuracy.

Paper selection

The paper presented in this seminar is: Meyer, et. al., "Normalized metal artifact reduction (NMAR) in computed tomography" published in *The International Journal of Medical Physics* in 2010. The purpose of this paper is to introduce a generalize normalization technique that will function as an extension of previously developed interpolation MAR techniques. This work presents and expands a vital technical aspect of out project: a step-by-step metal artifact removal computational algorithm. For our project, we will apply the MAR algorithm available in the Siemens Zeego workstation to the brain phantom images acquired. Understanding the algorithm, its segmentation and interpolation capabilities, will aid in the quantitative assessment of both the uncorrected and corrected data image quality. Currently, there are no clinical CT scanners providing metal artifact reduction software, and therefore, metal artifacts remain a major source of image degradation in CT guiding imaging. Further development and testing of research papers in this topic will hopefully lead MAR algorithms to clinical use availability.

Summary of problem

The presence of dense metal objects in the CT imaging field of measurement produces severe metal artifacts. These artifacts degrade the image quality and may render the image clinically and diagnostically useless. For example, metal artifacts caused by the presence of dental fillings may easily obscure low-contrast structures (e.g., tumors). Previously developed MAR techniques, such as sinogram inpainting methods, iterative methods, statistical methods, and filtering methods, have a few major drawbacks. First is the loss of metal edge information, which results in blurring of the corresponding edges in the image. Secondly is the unsmoothing of interpolated projection data, which cause the formation of streak artifacts tangent to metal objects. The problem, apart from the raw metal artifact, is the loss of information in the metal trace and hence the introduction of new artifacts from previously developed MAR techniques.



Shown above are four cases of metal artifacts produced by: #1 bilateral hip prostheses, #2 unilateral hip prosthesis, #3dental fillings and #4 rod for spine fixation. Image provided by Meyer, et.al.

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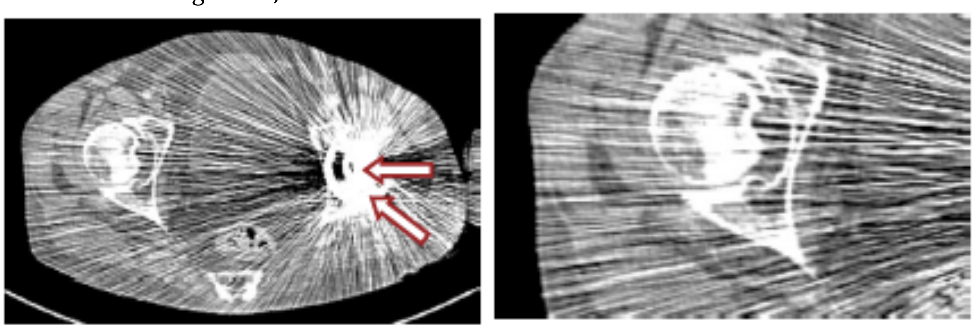
Key result and Significance

With the introduced denormalization technique, the NMAR algorithm restores traces of high-contrast objects in the metal shadow that were otherwise obscured or hidden in previous MAR algorithm applications. NMAR therefore provides an optimization of the image quality that facilitates a safer, more accurate use of CT imaging in the surgical environment.

Technical Background

X-ray computed tomography is a medical imaging modality that relies on the transmission of ionizing radiation through the body. Various tissues and organs within the body attenuate or decrease the intensity of the beam at varying rates. The most basic measurement of a CT scanner is a line integral of these linear attenuation coefficients. For a fixed angle, the measured linear attenuation of the object is called a *projection*. A *sinogram* is a rectilinear plot of the projections versus the angles they were acquired. It is a pictorial representation of the Radon transform of the signal, f(x,y) and represents the data necessary to reconstruct f(x,y). The reconstruction of object f(x,y) uses three basic steps to reconstruct an image from a sinogram: filtering, backprojection, and summation.

Metal artifacts on CT are produced by the presence of dense metallic objects. Artifacts are caused by: beam hardening phenomenon (shift in the exiting x-ray energy spectrum due to absorbance of low-energy photons), photon starvation (the complete absorbance of photons by the metal inhibits photons from reaching the detector), and attenuation artifacts (motion of the interface between the metal and surrounding tissue). They produce a streaking effect, as shown below.



Images of hip prostheses provided by Meyer et.a l.

Metal artifact removal techniques have been developed to reduce and/or remove metal artifacts. Among the most common techniques are: (a) Sinogram inpainting methods, which treat metal affected values as missing data and use interpolation or forward projections to complete the sinogram. (b) Filtering methods, which uses all the available information so as to not replace parts of projections. (c) Iterative methods, which provide a means of incorporating additional physics-related artifact knowledge. (d) Statistical methods, which are less sensitive to noise than filtered backprojection.

The paper adapts, applies and tests two previously developed techniques. The first one, dubbed MAR1, is a linear interpolation method, where metal objects are segmented by a thresholding operation in the uncorrected image. The metal trace is defined and replaced in the raw data. The second technique used, dubbed MAR2, is a length normalization method, where length normalization of the sinogram prior to interpolation is used to obtain better contrast between air and objects of water-equivalent material.

Theory

One problem with interpolation in the sinogram is the lack of smoothness of the transition region from original to interpolated data, which causes streak artifacts. Interpolation is less problematic in homogeneous data. The idea of a proper normalization is to transform the sinogram in a way that it becomes comparatively flat. If the interpolation is performed on a nearly flat, normalized sinogram, the transition between original data and interpolated values is very smooth.

Proposed Algorithm

1. Reconstruct uncorrected image from the original raw data.
2. Obtain metal image segmentation by a thresholding operation.
3. Compute prior image by segmentation of tissue and bone.
4. Apply forward projection to yield corresponding sinograms.
5. Normalize original sinogram by dividing it (pixelwise and with threshold so to not divide by zero) by the forward projected prior image. Note that, strictly speaking, only the values close to the metal trace need to be normalized and denormalized because only those contribute to the interpolation.
6. Apply an interpolation-based MAR operation to the normalized projections.
7. Obtain corrected sinogram by denormalization of the interpolated, normalized sinogram (the structure information from the prior image is brought back to the metal trace).
8. After reconstruction, insert metal segmentation back into the corrected image.

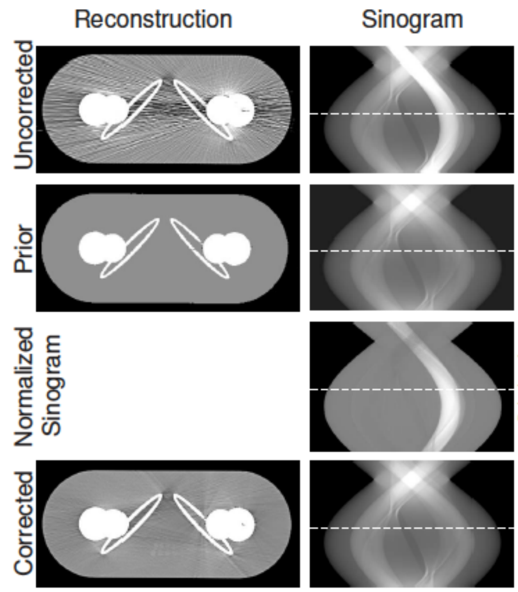


Image by Meyer et.al.

Parameters and Measurements

To evaluate the potential of NMAR, Meyer and her colleagues constructed and applied the NMAR algorithm to the CT images of two phantoms that simulated two different clinical situations where metal artifacts occur: hip replacement by titanium prostheses and spinal fusion using pedicle screws. To demonstrate the benefits of NMAR in comparison to the previously developed algorithms MAR1 and MAR2, the NMAR algorithm was applied to the CT scans of four patients. Patient 1 was a case with bilateral hip endoprostheses, patient 2 had one hip total endoprosthesis, patient 3 has metallic dental fillings, and patient 4 had a Harrington rod fixed to the spine. Unfortunately, the paper does not discuss any quantitative measurement of image quality or the NMAR segmentation accuracy; it solely relies on "visual inspection" (Meyer, 5490). This results in a subjective measurement of quality improvements, a problem discussed further on in this seminar.

Results

Results for the phantom simulations and the clinical data sets corrected with MAR1, MAR2, and NMAR, showed visual image quality improvement. More specifically,

- Hip phantom: MAR1 leads to severe blurring and streaking artifacts, MAR2 does not greatly differ from MAR1, and NMAR further reduces artifacts.
- Thorax phantom: MAR1 leads to severe blurring and streaking artifacts, MAR2 enhances image quality, and NMAR further reduces artifacts.
- Patient 1: When compared to MAR1 and MAR 2, only NMAR results in an image where almost no new streaks are introduced and also does not blur the region close to the implants.
- Patient 2: In the NMAR corrected image, blurring and streak artifacts are no longer visible.
- Patient 3: With NMAR, the image is restored even in regions close to the filling and the newly introduced artifacts are least prominent. Unfortunately, even with NMAR, some artifacts remain.
- Patient 4: Images from slices with only small metal implants, which only suffer from less severe artifacts, are not made worse than the uncorrected images. NMAR preserves all structures, as it uses the prior image, which is very accurate in these cases.

Positive/Negative Aspects of Paper

Perhaps the most important positive aspect of the introduced NMAR algorithm is the fact that it is meant to be used as an additional step to conventional sinogram inpainting methods. It attacks the problem of blurring due to loss of information of metal trace, which is a drawback that occurs in multiple MAR techniques. NMAR manages to restore traces of high-contrast objects in the metal shadow and leads to a more successful MAR application. It is computationally effective and inexpensive when compared to iterative methods. The paper is also effective in showing NMAR used in conjunction with both sinogram interpolation and linear interpolation techniques.

Unfortunately, the proposed NMAR method highly depends on an accurate segmentation operation of the metal object. This is a vital drawback because current segmentation techniques, especially the thresholding method used in the paper, are not perfectly accurate. Therefore, the segmentation becomes a substantial dependency. However, the greatest flaw of the paper is the lack of quantitative measurements of image quality. MAR1, MAR2 and NMAR processed data are measured “by visual inspection”: a subjective measurement that is not thoroughly explained in the paper. This might render their claims implausible.

Further Work

Faulty or inaccurate segmentation operations will negatively affect the proposed NMAR technique. A more advanced segmentation algorithm would surely enhance the results compared to simple thresholding. Current methods of medical image segmentation that prove to be more effective than thresholding include the use of uncertainty and optimization models, morphological analysis and partial volume averaging, among others. Segmentation algorithm improvement, though, is out of the scope of our CIS project work.

Apart from testing and selecting the most effective and efficient segmentation algorithm, NMAR could also be applied and tested along various MAR techniques to find the most effective and efficient combination. However, testing of the algorithm accuracy is still a rather subjective effort since it requires image quality assessments. Our CIS project aims to find a quantitative measurement of streaking artifacts and image quality in CT imaging before and after MAR applications.

Lastly, further clinical testing needs to be completed before MAR algorithms can be used as either diagnostic aids or vital components of CT image guidance systems.

Summary

Metal artifacts introduce image quality degradation and might render CT images diagnostically useless. Metal artifact removal/reduction (MAR) methods have been developed that partially removes metal streaking artifacts, but many introduce blurring artifacts as secondary effects. The proposed method of normalized metal artifact reduction (NMAR) is shown to reduce those newly introduced artifacts. Further work of quantitative testing and improvement of algorithms and image quality will produce more effective and efficient MAR methods that could provide real-time safe and accurate diagnostics and CT image guidance.