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Prior Image Constrained Compressed Sensing Metal Artifact Reduction (PICCS-MAR): 2D and 3D Image Quality Improvement with Hip Prostheses at CT Colonography

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Abstract

Purpose—To assess the effect of the prior-image-constrained-compressed-sensing based metal-artefactreduction (PICCS-MAR) algorithm on streak artefact reduction and 2D and 3D-image quality improvement in patients with total hip arthroplasty (THA) undergoing CT colonography (CTC).

Material and Methods—PICCS-MAR was applied to filtered-back-projection (FBP)-reconstructed DICOM CTC-images in 52 patients with THA (unilateral, n=30; bilateral, n=22). For FBP and PICCS-MAR series, ROI-measurements of CT-numbers were obtained at predefined levels for fat, muscle, air, and the most severe artefact. Two radiologists independently reviewed 2D and 3D CTC-images and graded artefacts and image quality using a five-point-scale (1=severe streak/no-diagnostic confidence, 5=no streak/excellent image-quality, high-confidence). Results were compared using paired and unpaired *t*-tests, Wilcoxon signed-ranks and Mann-Whitney-tests.

Results—Streak artefacts and image quality scores for FBP versus PICCS-MAR 2D-images (median: 1 vs. 3 and 2 vs. 3, respectively) and 3D images (median: 2 vs. 4 and 3 vs. 4, respectively) showed significant improvement after PICCS-MAR (all $P<.001$). PICCS-MAR significantly improved the accuracy of mean CT numbers for fat, muscle and the area with the most severe artefact (all $P<.001$).

Conclusion—PICCS-MAR substantially reduces streak artefacts related to THA on DICOM images, thereby enhancing visualization of anatomy on 2D and 3D CTC images and increasing diagnostic confidence.

Keywords

Metal artefact reduction; Computed tomography; CT; CT colonography; total hip arthroplasty

Introduction

With the continuing development of new state-of-the-art imaging equipment, the clinical use of computed tomography (CT) is increasing in all fields of radiology [1]. Unfortunately, CT images of patients with metallic implants can suffer from severe artefacts due to beam hardening in the form of bright streaks (erroneously elevated CT numbers) and dark voids (erroneously lowered CT numbers) [2; 3]. Other confounding factors that contribute to the visual representation of metal artefacts include scatter and amplified sharp change of absorption between metallic implants and soft tissue by the filtering step in the image reconstruction [2; 3]. These metal artefacts limit contouring of the tissue surrounding the metallic implants and may significantly reduce the diagnostic accuracy of CT imaging [4].

Despite recent advances in CT technology, metallic implant induced metal artefacts still presents a major challenge [5]. Different general strategies have been introduced to mitigate metal artefacts: One strategy is the recently introduced dual-energy CT technology [6; 7]. In a dual-energy CT, images with high effective energies (~100-200 keV) can be synthesized from the measured dual-energy CT data. These high-energy CT images contain less severe or no metal artefacts since they represent images generated from high-energy photons that were able to penetrate through the metallic implants. Another strategy is to use a metal artefact reduction (MAR) technique that replaces the erroneous or missing information in the projection data by linear interpolation. Other MAR techniques minimize the influence or weighting of the projection data contaminated by severe photon starvation in the CT image reconstruction process [8-12]. In this method, a “prior image” is used to flatten the sinograms. The missing information is then acquired by interpolation.

Previous frequency split normalized MAR (FSNMAR) techniques use a very flat prior image, which classifies an image into other soft tissue or bone classes [13]. In this paper we present a MAR technique that uses a recently described prior image constrained compressed sensing (PICCS) algorithm [14; 15] to generate the needed prior image with significantly improved soft tissues content with many different classes. After using the PICCS generated prior image to flatten the sinograms for data interpolation, the corrected sinograms were used to reconstruct the final metal artefacts corrected images. The algorithm was developed to directly work on the DICOM images, eliminating the need to access the raw projection and/or dual-energy data from the CT scanner. Thus the method is intended to be readily and also retrospectively applicable to any single kVp CT images without vendor limitations. For brevity, the developed metal artefacts reduction method is referred to as PICCS-MAR throughout the paper.

Reduced dose CT colonography (CTC) in patients with total hip arthroplasty (THA) represents an ideal testing ground for evaluating this PICCS-MAR algorithm. Both the pelvic organs on 2D CTC images and the rectal lumen on both 2D and 3D CTC images are directly subjected to the in-plane artefact from THA, in an area already constrained by the bony pelvis in terms of image noise and artefact (4, 5). The purpose of our study was to assess the effect of the PICCS-MAR algorithm on streak artefact reduction and 2D and 3D image quality improvement in patients with THA at CTC.

Material and Methods

Study population

This retrospective study received institutional review board approval and was Health Insurance Portability and Accountability Act compliant. The need for informed consent was waived. The study was performed by using the DICOM images from CTC data sets obtained in 52 adult patients with metallic total hip arthroplasty (THA). These DICOM data were retrieved from our PACS. THA was unilateral in 30 patients (57.7%) and bilateral in 22 patients (42.3%). The study group comprised 23 women and 29 men with an average age of 64 years (age range, 46-91 years).

CT Technique

All patients underwent standard cathartic regimes the day before the CTC examination, including oral contrast tagging [16]. Automated CO₂ delivery (PROTOCO₂L, Bracco) was used to achieve colonic distention [16]. CTC image acquisition was performed on 8-, 16- or 64-section multi-detector CT scanners (GE Healthcare, Waukesha, WI). Acquisition parameters consisted of 120 kVp, and static (40-100 mAs) or modulated tube current (NI=50; mA range = 30-300 mA). Two-dimensional (2D) DICOM CTC images were reconstructed with a 1-mm reconstruction interval using standard filtered back-projection (FBP) technique with the “Standard” GE reconstruction kernel, which has an intermediate sharpness between a soft tissue and lung kernel and is similar to the Siemens kernel B43f [17]. Three-dimensional (3D) CTC images were reconstructed with dedicated CTC software from the FBP DICOM data sets (V3D Colon; Viatronix, Stony Brook, NY).

Reconstruction Technique for PICCS-MAR

PICCS-MAR method is an in-house developed technique that combines the following four innovations for improved metal artefact reduction (MAR): (i) a pseudo-statistical model is introduced in the reconstruction step to reduce the photon starvation-related noise streaks; (ii) the recently described ‘Prior Image Constrained Compressed Sensing’ (PICCS) algorithm [14; 15] is used to reconstruct the ‘prior image’ for estimation of missing information (iii) after the missing information is estimated from the ‘prior image’, the PICCS reconstruction algorithm is applied again to reduce the residual streaks and reduce image noise; and (iv) the method is developed to directly work on the DICOM images. Except for these innovations, the workflow of the PICCS-MAR algorithm is the same as for those described in literature [8; 9]. The PICCS-MAR algorithm takes ~3 minutes to reconstruct the image volume of a CTC scan. 3D CTC images were generated from the supine 2D PICCS-MAR data sets with the same CTC software as for the FBP DICOM data sets.

Qualitative image analyses

To subjectively evaluate the artefacts and the diagnostic image quality, both 2D and 3D CTC data sets were reviewed independently by two abdominal radiologists ([reader 1, blinded for review] and [reader 2, blinded for review] with 8 and 15 years of experience, respectively). Blinded FBP and PICCS-MAR images were displayed in random order to the readers on a

dedicated CTC workstation (V3D Colon, Viatronix). Images were evaluated in the same soft tissue window settings (window level, 60 HU; window width, 340 HU).

The degree of the metal artefacts was scored on 2D and 3D images on a scale from 1 to 5 (1, very severe streaks; 2, severe streaks; 3, moderate streaks; 4, minimal streaks; 5, no streak artefact) [6; 18]. The diagnostic image quality at the level of the prostheses was scored on 2D and 3D images on a scale from 1 to 5 (1, severely reduced image quality, nondiagnostic; 2, markedly reduced image quality with impaired diagnostic interpretability; 3, acceptable image quality and diagnostic interpretability; 4, good image quality with high diagnostic confidence; 5, excellent image quality with full diagnostic interpretability)[18].

Quantitative image analyses

An abdominal radiologist ([reader 1, blinded for review]) obtained mean CT number and standard deviation (SD) values in Hounsfield units (HU) by placing a total of seven 100-150 mm² circular regions of interest (ROI) on both standard 2D FBP images and the 2D PICCS-MAR images (**Fig. 1**). The first ROI was placed at the location of the darkest THA induced streak artefact between the hips. Three ROIs were placed at the level of the THA induced streak artefacts in muscle, fat, and air (rectum). Three reference ROIs were placed in muscle, fat, and air (colon) at a level well above the THA that was not affected by artefacts. A total of 724 ROI-measurements were performed (362 from FBP images, 362 from PICCS-MAR images). To ensure matched ROI placement, the FBP and PICCS-MAR 2D images were displayed side-by-side on a CTC workstation without blinding the technique of the data sets (as it is obvious to the reader whether PICCS-MAR was applied to a DICOM data set or not). The reader carefully selected the location of each ROI without including adjacent organs or structures. Standard deviation of image pixel values inside the ROI corresponds to image noise [19].

Statistical Analyses

Medians and ranges of the subjective artefact and image quality scoring (for 2D and 3D images) were calculated for FBP and PICCS-MAR images. An average median score from both readers was calculated from the individual subjective scorings for further statistical analyses. Averaged median qualitative scores were calculated for the group of unilateral THA and the group of bilateral THA. Average Hounsfield Units (HU) of mean and standard deviation (SD) values of ROI measurements were calculated for FBP and PICCS-MAR 2D images.

Paired and unpaired *t* tests were used for comparison of HU values of ROI measurements. Wilcoxon signed-rank test (paired samples) and Mann-Whitney test (unpaired samples) was used for comparison of artefact and image quality scorings. Data were expressed as means $\pm$ one standard deviation (SD). The interobserver variability of subjective artefact and image quality scoring was evaluated by linear-weighted kappa statistics. A kappa value of 0–0.20 indicated slight agreement; 0.21–0.40, fair agreement; 0.41–0.60, moderate agreement; 0.61–0.80, substantial agreement; and 0.81–1.00, almost perfect agreement [20]. The 95%-confidence intervals (95%-CI) were provided for kappa values. A *P*-value of less than .05 indicated a statistically significant difference. Statistical computations and graphics were

performed with commercially available software (MedCalc Statistical Software version 12.7.5, MedCalc Software, Ostend, Belgium).

Results

Qualitative and Quantitative Image Analyses of 2D Images

Qualitative ratings of both readers judged the streak artefacts to be significantly lower on 2D images with PICCS-MAR reconstruction as compared to standard FBP images (3 vs. 1, $P < .0001$). Consistently, 2D image quality for PICCS-MAR images was improved over FBP in all patients (**Fig. 2**). The diagnostic quality of 2D images with PICCS-MAR reconstruction was significantly better than the standard FBP images (3 vs. 2, $P < .0001$). The artefacts and the image quality grades were significantly worse on both FBP and PICCS-MAR 2D images for the group of bilateral THA as compared to the group of unilateral THA (all $P < .001$) (**Table 1**). Importantly, none of the 2D data sets (both readers: 0/52; 0%) was rated as non-diagnostic at the level of THA after reconstruction with PICCS-MAR as compared to standard FBP reconstructed images (reader 1: 27/52; 51.9% and reader 2: 29/52; 55.8%). The linear-weighted kappa value for interobserver variability of the evaluation of streak artefacts and image quality of 2D data sets was 0.76 (95%-CI: 0.69 - 0.84) and 0.68 (95%-CI: 0.59 - 0.78), respectively.

Quantitative ROI measurements substantiated the qualitative image scores (**Table 2**). The mean attenuation of the most severe dark streak artefact was significantly increased from -514 HU on FBP images to -164 HU after PICCS-MAR reconstruction ($P < .001$). Also the mean attenuation of fat (-251 HU vs. -159 HU, $P < .001$) and of muscle (-227 HU vs. -7 HU, $P < .001$) at the level of the THA induced artefacts was significantly increased. The mean attenuation of air at the level of the artefacts was decreased (-852 HU vs. -872 HU), but this difference did not show statistical significance ($P = .11$). The mean CT numbers of fat, muscle, and colonic air above the level of the THA (not affected by the artefact, serving as reference tissues) were not significantly altered by the application of the PICCS-MAR reconstruction (all $P .05$) (**Fig. 3A, Table 2**).

The SD of CT numbers was significantly decreased for all for regions (most severe streak, fat, muscle, and air) at the level of the artefacts after PICCS-MAR reconstruction (all $P < .001$). Application of the PICCS-MAR reconstruction also significantly reduced the SD value of fat ($P < .001$) and muscle ($P < .001$) that were not affected by the artefacts. There was no significant change of the SD value of colonic air that was not affected by the artefacts ($P = .69$) (**Fig. 3B, Table 2**).

Qualitative Image Analyses of 3D images

Both readers judged the streak artefacts to be significantly lower on endoluminal 3D images with PICCS-MAR reconstruction as compared to standard FBP images (4 vs. 2, $P < .0001$) (**Table 1**). Consistently, quality of endoluminal 3D images was improved or equivalent for PICCS-MAR in all patients (**Fig. 4**). The diagnostic quality of endoluminal 3D images with PICCS-MAR reconstruction was significantly better than of the standard FBP images (4 vs. 3, $P < .001$). The artefacts and the image quality grades were significantly worse on both

FBP and PICCS-MAR 3D images for the group of bilateral THA as compared to the group of unilateral THA (all $P < .001$) (**Table 1**). Importantly, none of the 3D data sets (both readers: 0/52; 0%) was rated as non-diagnostic at the level of THA after reconstruction with PICCS-MAR as compared to standard FBP reconstructed images (both readers: 16/52; 30.8%). The linear-weighted kappa value for interobserver variability of the evaluation of streak artefacts and image quality of 3D data sets was 0.81 (95%-CI: 0.74 - 0.87) and 0.76 (95%-CI: 0.68 - 0.83), respectively.

Discussion

Our study revealed that the PICCS-MAR reconstruction effectively reduced metal streak artefacts on both 2D and endoluminal 3D images from single-energy CTC DICOM data sets in patients with THA. The PICCS-MAR reconstruction thereby improved the diagnostic quality of 2D and 3D CT images as compared to standard FBP data sets.

The PICCS-MAR algorithm allowed for a significant qualitative and quantitative reduction of metal artefacts on standard 2D CTC DICOM data sets with significantly improved diagnostic image quality. These 2D PICCS-MAR reconstructed data sets then allowed for reconstruction of 3D CTC images with significantly reduced artefacts and significantly higher diagnostic image quality. Albeit the overall image quality was improved after PICCS-MAR reconstruction, readers still judged that residual minor artefacts persisted in the CT images. After PICCS-MAR, the attenuation values of muscle and fat affected by the streak artefacts approached those of muscle and fat not affected by the artefact. However, there was still a significant difference in the mean HU values after PICCS-MAR reconstruction. These quantitative results underline that the PICCS-MAR algorithm cannot completely eliminate metal artefacts. Nevertheless, in all cases the image quality was improved or maintained, i.e. in none of the cases did the application of the PICCS-MAR algorithm lead to deterioration of the images. Indeed, after application of the PICCS-MAR algorithm none of 2D and 3D data sets was rated as non-diagnostic at the level of THA induced artefacts, which is in a clinical setting the key question with regard to metal-induced artefacts.

Previous studies have demonstrated other approaches to metal artefact reduction for CT [6-9; 21]. Normalized metal artefact reduction (NMAR) and frequency split MAR (FSMAR) can be applied retrospectively [8; 9]. However, many studies were performed with dual-energy CT techniques instead of single kVp ("single energy") techniques [6; 7]. These dual-energy CT techniques have to be prospectively applied to the split high-kVp and low-kVp source projections and cannot be applied retrospectively to standard DICOM data sets from PACS. Also, the previous studies focused on 2D images and did not assess the effect of the metal artefact reduction software on 3D endoluminal CTC projections. Here we have shown, that our PICCS-MAR algorithm allows for successful reduction of metal artefacts on standard DICOM CTC data sets from single kVp CT scans that were retrospectively retrieved from our PACS without the need for dedicated dual-energy CT techniques.

The applicability of the presented PICCS-MAR algorithm to single kVp CT DICOM images is of great relevance in a clinical context. Dual-energy CT scanners and the required dedicated metal artefact reduction software are not widely available and if available, data

have to be acquired prospectively. In contrast, our PICCS-MAR algorithm can be applied retrospectively to any DICOM data set from a standard single kVp CT scan. In addition, this algorithm is time efficient and does not require major computational resources. The PICCS-MAR algorithm takes ~3 minutes to reconstruct the image volume of a CTC scan, while FBP reconstruction takes less than 30 seconds. The PICCS-MAR technique is highly parallelized and the computational speed is potentially proportional to the number of CUDA (Compute Unified Device Architecture) cores of the graphics card. Therefore, the reconstruction time can be further reduced by adding a second graphics card. Furthermore, PICCS-MAR reconstruction can be performed offline without requiring any CT scanner time and can be easily incorporated into the daily clinical workflow. These advantages allow for a wider application at more sites. Moreover, it might foster the application for other anatomical sites such as the neck, where artefacts from dental implants may lead to a reduced diagnostic performance in patients with oropharyngeal cancer [4].

Previous studies have reported the occurrence of new artefacts (dark streaks) after application of their metal artefact reduction software [22-24] and Han et al. recommended reviewing both the images with and the images without MAR reconstruction to avoid missing focal lesions in the pelvic cavity [24]. However, we did not observe new severe or diagnosis-limiting streak artefacts after application of our PICCS-MAR algorithm to FBP images, albeit visually the attenuation was not uniform throughout a given tissue, such as fat. This is another indicator that the presented CS-MAR algorithm cannot completely eliminate metal artefacts.

There were limitations to our study. Since it was obvious to the readers whether PICCS-MAR was applied to a DICOM data set, it has to be acknowledged that this might have biased the subjective image analyses. Also, we did not compare our PICCS-MAR to another MAR-algorithm, which might have further demonstrated the potential improvement of PICCS-MAR. However, the aim of this study to evaluate the potential clinical impact of PICCS-MAR and not a technical comparison with other MAR- and or iterative reconstruction techniques [13; 25]. Further, we did not assess the effect of the PICCS-MAR algorithm upon actual colonic lesion detection on 2D or 3D images. However, since only in 10-15% of CTC screening examinations will have relevant polyps detected, a much larger study cohort would be needed to reliably detect a statistically significant difference. Also, further studies are needed to assess the usefulness of the PICCS-MAR algorithm for imaging in the direct vicinity of metallic implants to assess the periprosthetic bone and for CT protocols of other body regions.

In summary, the PICCS-MAR algorithm substantially reduces streak artefacts related to metal hip prostheses on DICOM data sets, thereby enhancing visualization of anatomy on 2D and 3D CTC images and increasing diagnostic confidence.

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Key Points

PICCS-MAR significantly reduces streak artefacts associated with total hip arthroplasty on 2D and 3D CTC.

PICCS-MAR significantly improves 2D and 3D CTC image quality and diagnostic confidence.

PICCS-MAR can be applied retrospectively to DICOM images from single-kVp CT.

Figure 1. CT colonographic images reconstructed with (A) filtered back projection (FBP) and (B) with PICCS-MAR algorithm

ROI locations are indicated at the level of the bilateral hip arthroplasty (upper panels) and above (lower panels) for quantitative measurements of tissues affected and non-affected by artefacts. The ROI for assessment of the most severe artefact was placed at the location of the darkest streak artefact between the hips (S). Parenchymal ROIs were placed in muscle (M) and fat (F). Air column ROIs (*) were placed in the rectum and colon, respectively. Level: 40 HU, width: 350 HU.

Figure 2. Comparison of two-dimensional CT colonographic images

(A) FBP and (B) PICCS-MAR reconstructed images. Unilateral metal hip arthroplasty (upper panels) shows less artefacts and than bilateral metal hip arthroplasty (lower panels). In both cases streak artefacts were reduced and the diagnostic image quality improved after PICCS-MAR reconstruction. Note the improved conspicuity of the separation of the uterus (asterisk) and bladder (arrowhead) after PICCS-MAR reconstruction. Level: 40 HU, width: 350 HU.

Figure 3. Improvement of objectively measured attenuation values

(A) Means and (B) standard deviations of attenuation values of images reconstructed with filtered back projection (FBP) and with prior image constrained compressed sensing based metal artefact reduction ((PICCS)-MAR) for the most significant artefact zone adjacent to the metal implant, fat, muscle and colonic air. Mean and standard deviation values of fat, muscle and colonic air affected by the streak artefact (streak) are shown in comparison to values of the respective tissues not affected by the artefact (reference).

Figure 4. Comparison of three-dimensional CT colonographic images
(A) FBP and (B) PICCS-MAR reconstructed images with matching orientation. Unilateral metal hip arthroplasty (upper panels) shows less artefacts than bilateral metal hip arthroplasty (lower panels). In both cases streak artefacts within the colonic air were reduced and the diagnostic image quality improved after PICCS-MAR reconstruction. Note the improved conspicuity of the catheter after PICCS-MAR reconstruction.

Table 1
Qualitative Two- and Three-dimensional Artifact and Diagnostic Image Quality Scores

Qualitative Rating	Technique	Two-dimensional Imaging						Three-dimensional Imaging																	
		Overall (n=52)			Unilateral THA (n=30)			Bilateral THA (n=22)			P value†			Overall (n=52)			Unilateral THA (n=30)			Bilateral THA (n=22)			P value†		
		median	range		median	range		median	range		median	range		median	range		median	range		median	range		median	range	
Artifact Scoring	FBP	1	(1 - 3)	2	(1 - 3)	1	(1 - 2)	<.0001	2	(1 - 5)	3	(1 - 5)	1	(1 - 3)	<.0001										
	PICCS-MAR	3	(1 - 4)	3	(2 - 4)	2	(1 - 4)	=.0001	4	(2 - 5)	5	(3 - 5)	3	(2 - 4)	<.0001										
	P value*	<.0001		<.0001		<.0001		<.0001	<.0001		<.0001		=.0001		<.0001		=.0001		<.0001						
Image Quality	FBP	2	(1 - 3)	2	(1 - 3)	1	(1 - 2)	<.0001	3	(1 - 5)	4	(1 - 5)	2	(1 - 4)	<.0001										
	PICCS-MAR	3	(1 - 5)	3	(1 - 5)	2	(1 - 4)	=.0003	4	(2 - 5)	5	(3 - 5)	3	(2 - 5)	<.0001										
	P value*	<.0001		<.0001		<.0001		<.0001	<.0001		<.0001		=.0001		<.0001		=.0001		<.0001						

Note. - P values < .05 indicate statistical significant differences between ratings of FBP and CS-MAR reconstructions* and between unilateral and bilateral THA[†]. FBP, filtered back projection, PICCS-MAR, prior image constrained compressed-sensing metal artifact reduction; THA, total hip arthroplasty. Artifact scoring 1 = very severe streaks to 5 = no streak artifacts. Image quality grading: 1 = severely reduced image quality to 5 = excellent image quality.

Table 2

Means and Standard Deviations of ROI Attenuation Measurements

Attenuation (HU)	Technique	Worst Streak			Fat tissue			Muscle tissue			Colonic Air		
		Fat	Fat Reference	P value†	Muscle	Muscle Reference	P value†	Air	Air Reference	P value			
Mean	FBP	-514 ± 189	-251 ± 81	-103 ± 7	<.001	-227 ± 97	43 ± 10	<.001	-852 ± 71	-987 ± 10	<.001		
	PICCS-MAR	-164 ± 72	-159 ± 57	-104 ± 7	<.001	-7 ± 48	42 ± 10	<.001	-872 ± 59	-986 ± 10	<.001		
	P value*	<.001	<.001	.46	<.001	.64	.11	.82					
Standard Deviation	FBP	140 ± 49	74 ± 86	44 ± 13	<.001	111 ± 54	50 ± 14	<.001	51 ± 22	21 ± 7	<.001		
	PICCS-MAR	55 ± 68	40 ± 15	34 ± 11	.048	38 ± 14	34 ± 13	.17	32 ± 13	21 ± 6	<.001		
	P value*	<.001	<.001	<.001	<.001	<.001	<.001	.69	<.001				

Note. - P values < .05 indicate statistical significant differences between FBP and CS-MAR reconstructions* and between tissues affected and tissues non-affected by streak artefacts†. FBP, filtered back projection; PICCS-MAR, prior image constrained compressed-sensing metal artifact reduction.