



Dual-layer spectral computerized tomography for metal artifact reduction: small versus large orthopedic devices

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Abstract

Introduction Metal artifacts limit the diagnostic utility of computerized tomography (CT) for implant-related complications. Dual-layer spectral detector CT imaging has been suggested for artifact reduction. Our objective was to evaluate the utility of spectral CT in artifact reduction in patients with small and large metal implants.

Methods In this prospective study, patients with metallic orthopedic implants underwent CT imaging using a prototype spectral detector CT scanner. Conventional images were generated with iterative reconstruction at 120 kVp, and virtual monochromatic images were generated at 20-keV intervals between 40 to 200 keV. Conventional and monochromatic images were compared quantitatively using signal-to-noise ratio (SNR) and artifact improvement. Qualitative analysis was performed independently by two musculoskeletal radiologists and included six image quality indicators.

Results A total of 12 patients were scanned. In monochromatic images, as the energy level increased, the artifact size decreased progressively ($p < 0.01$). When conventional and monochromatic images were compared, maximum reduction was seen at 200 keV. Using qualitative assessments, 160 and 180 keV levels had the best overall diagnostic image quality. With increased energy level, there was improvement in qualitative ratings of bone-metal interface conspicuity ($p = 0.002$), degree of streak artifact ($p = 0.010$) and trabecular bone definition at 1 cm from implant ($p = 0.023$), and a trend towards significance for bone definition at 5 cm, soft tissue detail and overall diagnostic quality. Subgroup analysis revealed superior artifact reduction in small implants compared to large hardware.

Discussion Our results support the utility of dual-layer spectral CT in metal artifact reduction. Virtual monochromatic images were diagnostically superior, especially for smaller implants. Virtual monoenergetic images at 160–180 keV are ideal for reducing artifacts.

Keywords Dual-energy computed tomography · Dual-layer detector · Artifact · Metal implant · Virtual monoenergetic images · Hip replacement arthroplasty · Spinal instrumentation

Introduction

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Computerized tomography (CT) imaging is pivotal in orthopedic practice, particularly in diagnostic work-up, treatment planning and post-operative follow-up. Metal artifacts such as beam hardening, photon starvation and scatter artifacts limit the utilization of CT imaging in diagnostic work-up of implant-related complications and hinder accurate decisions for revision surgery. Furthermore, such artifacts limit the diagnostic utility of CT imaging in non-orthopedic pathologies in vicinity of metal implants. The increasing trend of joint replacement surgery is a good indicator of the extent of this problem. For instance, it was estimated that 4.7 million individuals lived in the US with an artificial knee in 2010, with prevalence rates as high as 10.13% in older age groups and

increasing trends due to population aging [1]. Therefore, with growing number of patients with artificial joints, poor image quality due to metal artifacts in non-orthopedic imaging examinations has become a common scenario.

Several options are available for artifact reduction in CT imaging. Proper implant positioning and exclusion of implant from the region of interest have been suggested for ankle and knee implants [2, 3]. While technologically undemanding, these options are not always possible. With advent of imaging technology, other measures have been introduced for metal artifact reduction, from optimization of CT acquisition parameters such as increasing the peak tube voltage, to more sophisticated post-imaging processing techniques [4]. Yet, implant-related artifacts remain a challenge in daily practice.

X-ray attenuation results from the interaction between material and x-ray beam, which is primarily explained by photoelectric and Compton phenomena in CT imaging [5]. In addition to the characteristics of the material under study, the beam-material interaction is affected by the energy level of the x-ray beam, especially for materials with high atomic numbers compared to the soft tissue [5]. There is an inverse non-linear relationship between the energy level of photons and attenuation of the X-ray beam. In conventional CT imaging, quality of the x-ray beam is determined by kilovoltage peak (kVp) value, which indicates the highest energy level of photons in the beam [6, 7]; however, the x-ray source is indeed comprised of photons with a variety of energy levels [6, 7]. When passing through the object, low energy photons are easily attenuated [6, 7]; therefore, resulting polychromatic images may contain dark streaks between metal objects, causing significant artifact [8].

Virtual monochromatic images (VMI) are images that mimic those obtained at single energy levels. These can be generated in dual-energy or spectral CT technologies using a process of linear combination of low and high energy basis images at different ratios [6, 7]. The energy levels of VMI are described in kiloelectronvolts (keV) and are typically generated from 40 to 200 keV. VMIs at high energy levels, i.e. >70 keV are known to be associated with lower artifacts. The earliest dual-energy CT technology used two consecutive image acquisitions at different energy levels (i.e. low and energy). However, this was limited by motion and different phase of contrast enhancement between the two acquisitions [9]. Currently available dual energy and spectral CT technologies include dual-source, rapid-kVp switching and a detector-based dual-layer spectral detector technology [10]. A simple way to perform dual energy CT is to perform consecutive image acquisitions using high- and low- kVp beams. This is however limited by artifacts related to motion and different phases of contrast enhancement for the two acquisitions. In the rapid kVp-switching technology, the tube voltage alternates between high- and low-energy beams for each gantry rotation within a fraction of a second, thus generating two

views per gantry rotation [10]. Dual-source dual-energy CT utilizes a similar concept using two separate x-ray tubes operated at high- and low-kVp energy levels [11]. Dual-layer detector technology is the most recent advancement, and is now available for clinical use. In this technology, the detector consists of two separate inner and outer layers which make it capable of simultaneously registering two high- and low-energy data sets from the spectrum of projected X-rays [12]. This technology diminishes the chronological mismatch between the high- and low-energy data sets, minimizing the motion-related misregistration attributed to conventional and rapid kVp switching CT methods [12].

The main objective of this study was to evaluate the utility of dual-layer spectral CT compared to conventional polychromatic CT in reduction of artifacts caused by small and large metal implants, particularly by (1) quantitative measurement of signal-to-noise ratio (SNR) and artifact size and (2) qualitative assessment of image quality indices by experienced musculoskeletal radiologists.

Patients and methods

This study was designed in compliance with Health Insurance Portability and Accountability Act (HIPAA) and the protocol was approved by our institutional review board (IRB No. 08–13-12). Informed consent was obtained from all the included patients.

Study population

The study included consecutive patients with metallic orthopedic implants who were scanned at our institution in the dual-layer CT scanner. CT scans of the neck, thorax, abdomen and extremities, which contained orthopedic metal implants, were included in the study. For definition of device size, implants used for hip or shoulder arthroplasty were considered ‘large’, and those used for other purposes such as spinal fusion were considered ‘small’. Examinations were performed for several clinical indications, including assessment of abdominal pain, renal or liver mass evaluation, shoulder or hip pain after arthroplasty, vascular lesions and pre-aortic valve placement evaluation.

Scanning technique

All scans were performed on a prototype spectral detector CT scanner (Philips Healthcare, Cleveland, Ohio, USA) that had two detector layers: the top layer constructed with 1-mm Yttrium-based garnet scintillator; and the bottom layer composed of gadolinium oxysulphide. Patients were scanned under different protocols, including seven upper extremity (shoulder) CTs without contrast, 2 routine abdominal CTs

with and without contrast, 1 CT angiography, 1 transcatheter aortic valve implantation and one pelvic CT without contrast. The dose and timing of contrast administration varied in different examinations depending on the protocol, body mass index and renal function. Either Isovue 370 (Bracco Diagnostics Inc., Princeton, NJ) or Ultravist 350 (Bayer Healthcare, Wayne, NJ, USA) were used with contrast doses ranging from 40 to 150 ml. Since 120 kVp is the minimal tube voltage required for spectral image generation in the SDCT, this tube voltage setting was used for all patients, with mAs adapted to the body size and automatic tube current modulation. In patients whose body mass index was low enough to allow the use of 100 kVp in a conventional equivalent scanner, the mAs was reduced to maintain dose neutrality (i.e., matched CTDIvol) with the same protocol in a conventional 256-slice CT scanner (Brilliance ICT, Philips). The detector configuration was 64×0.625 mm. The pitch ranged from 0.5 to 1.17 and gantry rotation time ranged from 0.3–0.75 s depending on the clinical indication.

Image generation

Conventional polyenergetic images at 120 kVp were generated with iterative reconstruction (iDose4 Level 3, Philips, Cleveland OH, USA), by using data from both detector layers. CT images were reconstructed at 2 mm thickness with 1 mm overlap with a B (standard) filter. The virtual monochromatic images (VMIs) were generated from spectral raw data at

energy levels ranging from 40 to 200 keV at 20-keV intervals using a dedicated workstation (Intellispace Portal, Philips Healthcare, The Netherlands). These VMIs were also reconstructed at 2-mm thickness and 1-mm overlap, with the B (standard) filter.

Quantitative image analysis

Image analysis was performed on a separate workstation (thin-client Spectral Diagnostic Suite of Applications, Philips Healthcare). In all, 120 kVp polyenergetic images with iterative reconstruction (iDose4) were compared to virtual monoenergetic (MonoE) reconstructions from 40 to 200 keV at 20-keV interval for each metal implant. The device size was measured and the regions of interest (ROIs) were placed in bone window (width 2000 HU, center 250 HU) on a representative axial plane (2-mm slice thickness): within the most evident streak artifacts on every image, soft tissue without artifact (muscle), and bone-metal interface on conventional 120-kVp images. The size of each ROI was 1 cm^2 , except in the smaller structures, in which case the largest possible ROI was placed. The ROIs were then copied to the 40–200 keV VMIs to ensure constant size and location of the ROIs. For SNR calculation, the signal was calculated as the mean HU within the ROIs and noise was calculated as the standard deviation of the pixel values. The SNR was then calculated by dividing the CT attenuation values by the corresponding image noise. This analysis was repeated for VMIs at all energy

Table 1 Five-point scale used in rating of image quality assessment

Quality variable	Five-point scale
Conspicuity of metal-bone	1. Not visualized
Trabecular bone definition, 1 cm from metal implant	2. Faintly visualized, not adequate for diagnosis
Trabecular bone definition, 5 cm from metal implant	3. Adequate
	4. Good
	5. Excellent
Degree of streak artifact	1. Extensive artifacts
	2. Pronounced
	3. Minor streaks, everywhere
	4. Minor streaks, only at thickest portions
	5. No artifact
Overall soft tissue detail	1. Inadequate
	2. Barely adequate
	3. Adequate
	4. Good
	5. Excellent
Overall diagnostic evaluation	1. Insufficient for diagnosis
	2. Restricted diagnosis
	3. Minor artifact, with some impact on diagnosis
	4. Minor artifacts, without impact on diagnosis
	5. Fully diagnostic

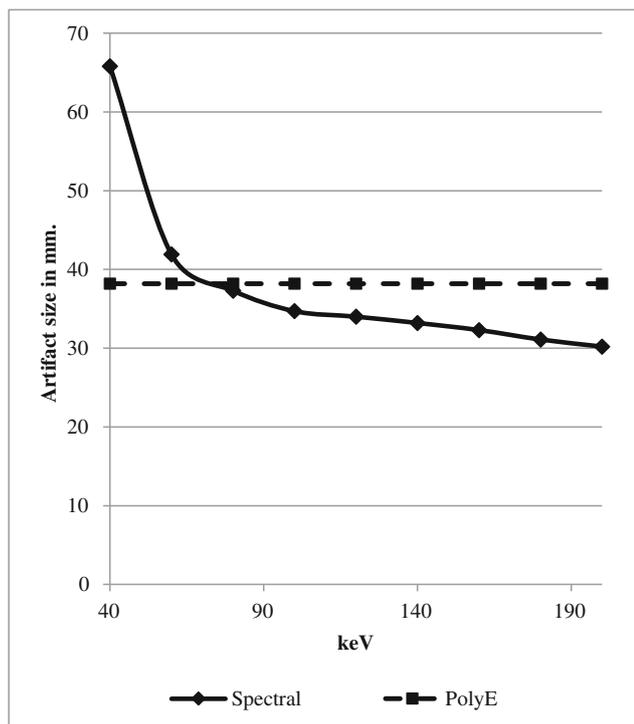


Fig. 1 Comparison of artifact size There was a reverse exponential reduction in artifact size in virtual MonoE spectral CT images (solid line) compared to the conventional polychromatic images (dashed line)

levels. Quantitative artifact intensity was defined as normal tissue HU minus average artifact HU. Artifact improvement was defined as (artifact size in polychromatic minus artifact size in monochromatic)/artifact size in polychromatic \times 100.

Qualitative image analysis

Image analysis was performed on the same workstation (Philips) by two independent musculoskeletal radiologists (PY and CK), both of which had more than 7 years of experience in musculoskeletal imaging. Prior to qualitative assessments, all image identifiers and acquisition data were removed, and the order of images was randomized. The radiologists were blinded to the quantitative results and energy levels of the images. The default window settings of images were preselected at window width of 2,000 HU and window level of 250 HU; however, the radiologists were allowed to scroll through the sets of images and change window and/or level settings, as desired. Images of different energy levels of each patient were displayed randomly on a single screen. Each radiologist independently assigned a subjective score to each image using a 5-point Likert scale regarding six different variables of image quality: (1) conspicuity of metal-bone-interface, (2) degree of streak artifact, (3) and (4) trabecular bone

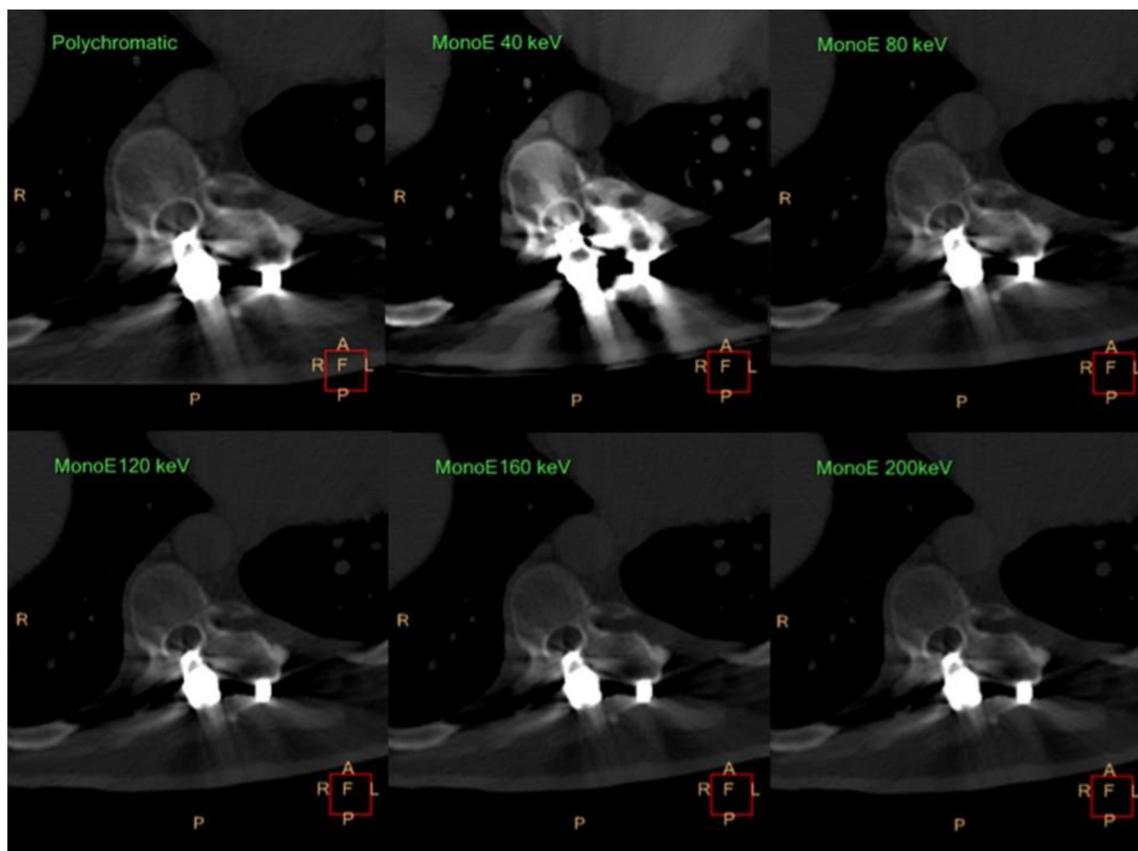
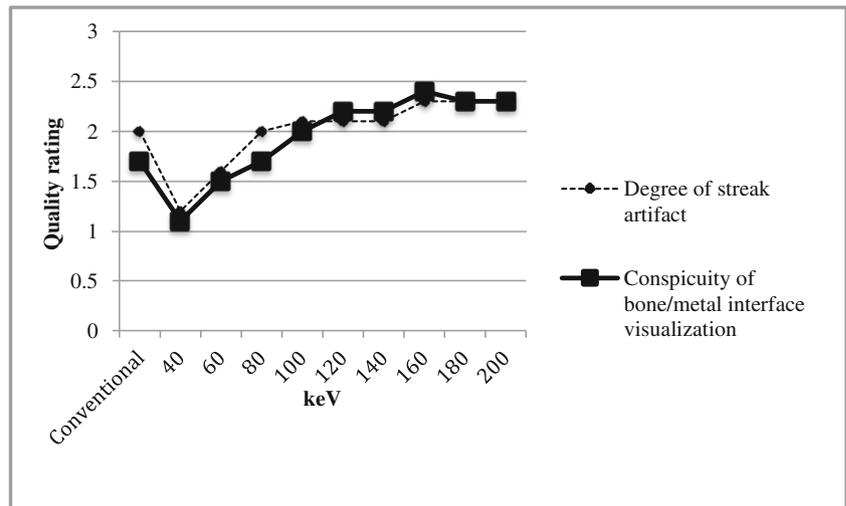


Fig. 2 There was a progressive reduction of artifact size in virtual MonoE spectral CT images compared to the conventional polychromatic images (60, 100, 140 and 180 keV images are omitted)

Fig. 3 Qualitative rating of conspicuity of bone-metal interface visualization and degree of streak artifacts in virtual MonoE spectral CT images compared to the conventional polychromatic images



visualization at 1 cm and 5 cm from metal device respectively, (5) overall soft tissue details and (6) overall image quality evaluation. The scores are described in detail in Table 1. When there was disagreement between the ratings, the images were reassessed by the two musculoskeletal radiologists to reach consensus.

Statistical analysis

All data were presented as mean \pm SD. Statistical analysis was performed using SPSS v. 24 (IBM Corp., Armonk, NY, USA). Weighted kappa analysis was used to evaluate the inter-rater agreement of qualitative ratings between the two reading radiologists [13]. Weighted kappa is considered a robust method for this purpose, and values were interpreted according to Altman's criteria [14, 15]. The SNRs and image quality scores across different energy levels were analyzed by two-sided

Kruskal-Wallis test. Comparison of indices by specific KeV levels with corresponding conventional level index value was conducted by first subtracting the conventional value from the KeV level value. These difference values were then assessed with a two-sided Wilcoxon signed rank test, to test whether difference values were significantly different from zero. A *p*-value of less than 0.05 was considered statistically significant and adjustment for multiple comparisons was not implemented.

Results

A total of 12 patients (33.3% men) with mean age of 64.17 years were included, with a total of 15 metallic orthopedic devices in the shoulder (7/15, 46.7%), hip (5/15, 33.3%) and spine (3/15, 20%).

Fig. 4 Qualitative rating of trabecular bone definition at 1 and 5 cm from the metal implants in virtual MonoE spectral CT images compared to the conventional polychromatic images

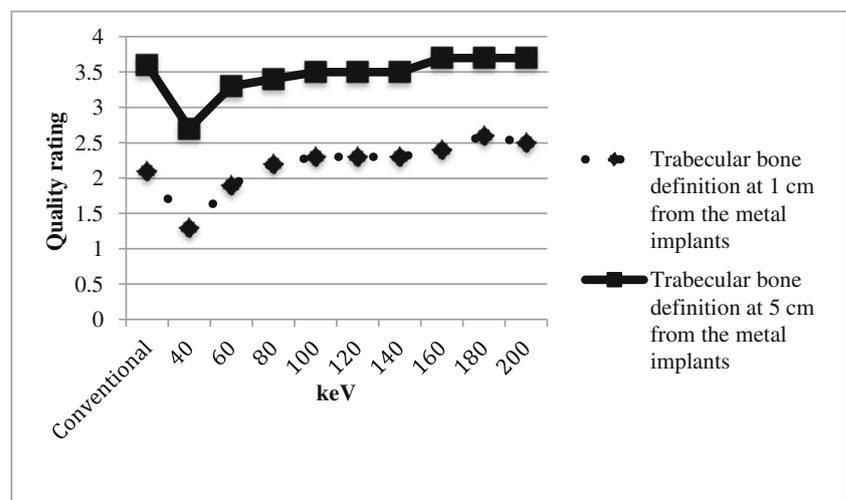
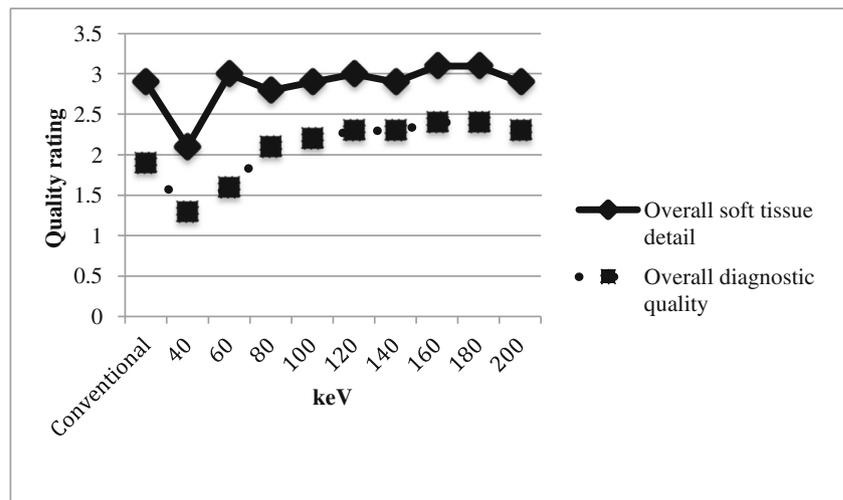


Fig. 5 Qualitative rating of overall soft tissue detail and overall diagnostic quality in virtual MonoE spectral CT images compared to the conventional polychromatic images



Quantitative analysis

The average artifact size in the 120 kVp polychromatic images was 38.2 ± 26.5 mm. There was a reverse exponential decrease in artifact size in VMIs ($p < 0.01$, Figs. 1 and 2). When compared to polychromatic 120 kVp images, improvement in artifact was identified starting at 80 keV (2.4% reduction with average artifact size of 37.3 ± 26.7 mm) to a maximum improvement at 200 keV (20.9% reduction with average artifact size of 30.2 ± 25.1 mm). No statistically significant difference was identified between different virtual MonoE images and conventional polychromatic images regarding the SNR of surrounding soft tissues ($p = 0.99$), SNR of bone-metal interface ($p = 0.499$) or SNR of streak artifacts ($p = 0.737$).

Qualitative analysis

The two reading radiologists had similar scores in 820 out of 900 ratings (91.1%), with a kappa value of 0.953 (SE = 0.006, 95% CI: 0.941–0.965). The level of agreement was

interpreted as ‘very good’. In VMI spectral CT images, there was a progressive improvement in qualitative rating of conspicuity of bone-metal interface visualization ($p = 0.002$; Fig. 3) as well as degree of streak artifacts ($p = 0.010$; Fig. 3). Compared to the other monochromatic energy levels and polychromatic 120 kVp images, the 40 and 80 keV levels demonstrated the worst ratings, while 160 keV level demonstrated the best. Regarding the trabecular bone definition, there was a statistically significant progressive improvement at 1 cm from the metal implants ($p = 0.023$; dashed line in Fig. 4), with the best definition identified at 180 keV. However, no significant change in the definition at 5 cm from the metal implant was seen among monochromatic energy levels ($p = 0.092$, solid line in Fig. 4), except for degraded trabecular bone definition at the 40 keV level. While there was no significant improvement in overall soft tissue detail analysis between monochromatic energy levels and conventional polychromatic images ($p = 0.11$; solid line in Fig. 5), at monochromatic image levels of 160 and 180 keV, the overall diagnostic image quality was superior to conventional polychromatic and other virtual MonoE images ($p = 0.10$; dashed line in Fig. 5).

Fig. 6 Subgroup analysis (small versus large device) regarding qualitative rating of conspicuity of bone-metal interface visualization and degree of streak artifacts in virtual MonoE spectral CT images compared to the conventional polychromatic images

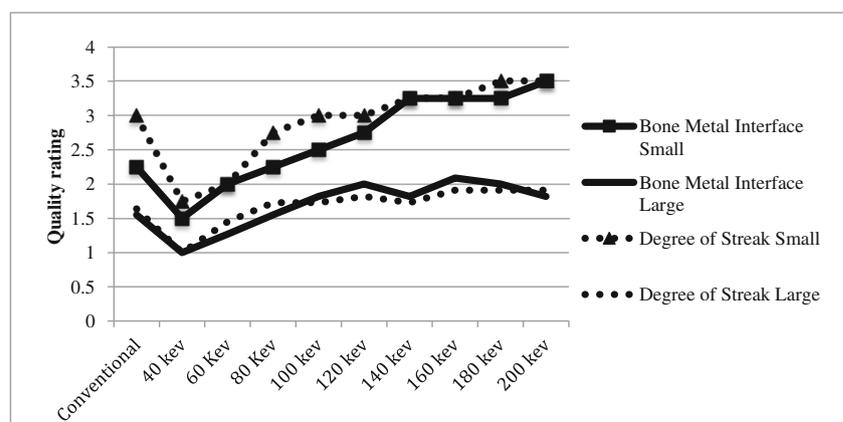
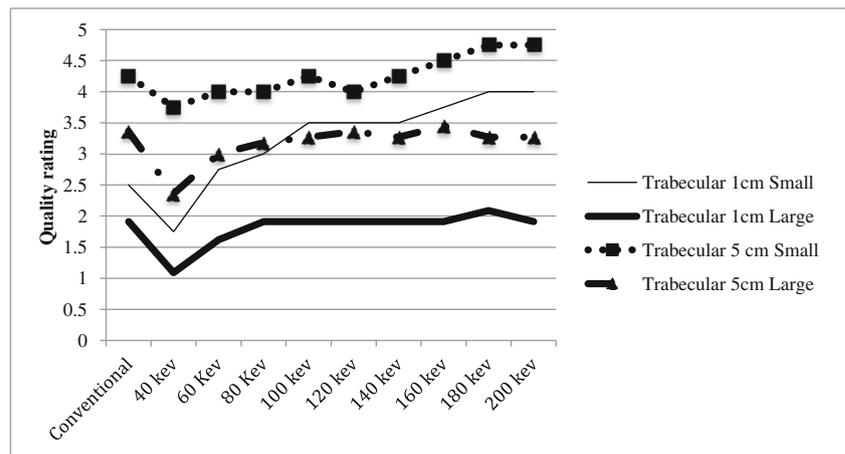


Fig. 7 Subgroup analysis (small versus large device) regarding qualitative rating of trabecular bone definition at 1 and 5 cm from the metal implants in virtual MonoE spectral CT images compared to the conventional polychromatic images



Subgroup analysis (small versus large devices)

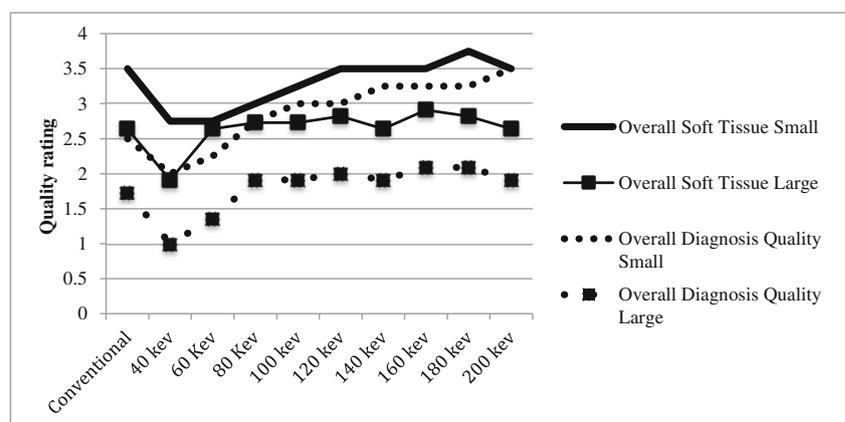
Comparison of the qualitative image rating was performed between the two groups of small versus large devices. In all monochromatic energy levels, small devices had higher ratings in all six qualitative indices of image quality compared to the large devices (Appendix and Figs. 6, 7 and 8). When VMI CT images of large devices were compared to conventional images, improvements in qualitative assessments were non-significant. However, there was a significant or nearly significant improvement in three out of six qualitative image indices of small devices, with the best ratings identified at the highest monochromatic energy levels of 160–200 keV (Figs. 6, 7 and 8). Specifically, conspicuity of bone-metal interface, at keV levels of 140, 160, and 180 was significantly greater than conventional (p -values = 0.046). At keV level of 200, the positive difference from conventional was nearly significant (p = 0.059). Other significant or nearly significant positive differences from conventional levels were as follows: trabecular definition at 1 cm from implant at 100 keV (p = 0.046) and 200 keV (p = 0.059); trabecular definition at 5 cm from implant at 160 keV (p = 0.059), 180 and 200 keV (p = 0.063);

and the overall diagnostic quality at 140, 160 and 180 keV (p = 0.083).

Discussion

This study investigated the value of detector-based dual-layer spectral CT in reducing the artifacts caused by small and large metallic orthopedic devices. Qualitative analysis in our study confirmed the superior diagnostic quality of virtual monochromatic reconstructions compared to polychromatic images, especially at 160–180 keV levels. Metal artifacts commonly hinder the accurate diagnosis of implant-related complications and non-orthopedic pathologies in CT imaging. Therefore, in patients with metal implants, effective artifact reduction improves conspicuity of peri-implant tissue and in part the diagnostic value of CT imaging. Based on our findings, metal artifacts were effectively reduced in virtual MonoE reconstructions when compared to conventional polychromatic images. Our quantitative analysis revealed a maximum reduction of 20.9% in artifact size at 200 keV in comparison to 120 kVp polychromatic images.

Fig. 8 Subgroup analysis (small versus large device) regarding qualitative rating of overall soft tissue detail and overall diagnostic quality in virtual MonoE spectral CT images compared to the conventional polychromatic images



Optimal monochromatic keV

Based on our qualitative assessment, 160 and 180 keV levels had the best overall diagnostic image quality compared to other virtual monochromatic and conventional polychromatic images. Similar photon energy level (180 keV) has been suggested as the optimal monochromatic setting for metal artifacts due to instrumented spinal fusion [16]. Other studies determined lower energy levels for optimal image quality, ranging from 110 to 130 keV for distal radius implants and an average level of 149.2 keV in a mixed population of orthopedic patients [17, 18]. These differences may stem from the differences in scanner technologies, differences in decomposition and reconstruction algorithms, differences in implant sizes and composition as well as subjective nature of qualitative assessments.

Utility of dual-layer spectral CT in metal artifact reduction

Studies on application of dual-layer spectral CT for reduction of metal artifacts are scarce; nevertheless, the body of evidence is rapidly growing. In the first application of this technology for metal artifact reduction, Wellenberg et al. compared the 200 keV monochromatic images with reference polychromatic images using various configurations of a phantom model of hip prosthesis [6]. Using dual-layer spectral CT, they found significant improvements in terms of noise, contrast-to-noise-ratios, SNRs and CT number accuracy [6]. These findings were confirmed by a clinical study on patients with total hip implants [19]; similar to our results, Laukamp et al. found a significant decrease in artifact size of virtual monochromatic images starting at 80 keV level and maximizing at 200 keV, with similar findings with respect to artifact density [19]. This decrease in artifact size at high energy levels was confirmed in another study, showing at least 50% decrease in artifact width in the majority of the images when 200 keV virtual monochromatic images were compared to reference conventional images [17]. Other studies have utilized dual-layer spectral CT in the clinical settings for evaluation of other orthopedic implants such as distal radius and spinal instrumentation, as well as non-orthopedic implants, including deep brain stimulation electrodes and dental implants [16, 18, 20, 21]. Our study supports the current evidence in favor of dual-layer spectral CT with regard to metal artifact reduction.

Small versus large devices

Our results revealed that in all monochromatic energy levels as well as conventional polychromatic images, small devices caused less artifacts compared to large devices. According to our findings, the severity of metal-induced artifact was dependent upon the size of the device, a known fact consistent with prior reports. While our sample size was limited to only four implants in the small device subgroup, these preliminary results give promising indication that qualitative indices improve with higher keV levels. More importantly, we found that spectral CT is more helpful in reduction of metal-induced artifacts when the device size is small. In this setting, the higher monochromatic energy levels provided the best readings.

Study limitations

Our study has several limitations. First of all, we performed a small number of cases and larger case series may prove useful to reaffirm our results. In addition, we did not have access to iterative reconstruction metal artifact reduction software on our system. Adding such software may improve the diagnostic efficiency and image quality of spectral detector CT images. Finally, in addition to quantitative measurements, qualitative indices were used in this study. Although the two musculoskeletal radiologists had nearly perfect agreement in qualitative ratings, such assessments may introduce certain degree of subjectivity.

Conclusion

Current study evaluated the utility of dual-layer spectral CT in reduction of artifacts caused by small and large metal implants. Based on our quantitative and qualitative assessments, dual-layer spectral CT is a promising modality for metal artifact reduction, especially for smaller implants.

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Compliance with ethical standards

Conflict of interest Author CK receives consulting fees from Bioclinica. Authors MH, AG, AA, PCY and PR declare they have no conflict of interest.

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