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Research paper

Metal artifact reduction by dual-layer computed tomography using virtual monoenergetic images

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ABSTRACT

Objective: The aim of the study was to investigate the performance and diagnostic value of metal artifact reduction in virtual monoenergetic images generated from dual-layer computed tomography (DLCT).
Methods: 35 patients that received a DLCT at the University Hospital Cologne and had an orthopedic implant in the examined region were included in this study. For each DLCT virtual monoenergetic images of different energy levels (64 keV, 70 keV, 105 keV, 140 keV, 200 keV and an optimized photon energy) were reconstructed and analyzed by three blinded observers. Images were analyzed with regard to subjective criteria (extent of artifacts, diagnostic image quality) and objective criteria (width and density of artifacts).
Results: 21 patients had implants in the spine, 8 in the pelvis and 6 patients in the extremities. Diagnostic image quality improved significantly at high photon energies from a Likert-score of 4.3 (± 0.83) to 2.3 (± 1.02) and artifacts decreased significantly from a score of 4.3 (± 0.66) to 2.6 (± 2.57). The average optimized photon energy was 149.2 ± 39.4 keV. The density as well as the width of the most pronounced artifacts decreased from −374.6 ± 251.89 HU to −12.5 ± 205.84 HU and from 14.5 ± 8.74 mm to 6.4 ± 10.76 mm, respectively.
Conclusion: Using virtual monoenergetic images valuable improvements of diagnostic image quality can be achieved by reduction of artifacts associated with metal implants. As preset for virtual monoenergetic images, 140 keV appear to provide optimal artifact reduction. In 20% of the patients, individually optimized keV can lead to a further improvement of image quality compared to 140 keV.

1. Introduction

Computed tomography (CT) is commonly used to evaluate orthopedic metal implants [1,2]. Artifacts caused by metal implants impair image quality and may obscure or simulate pathology [3]. Due to the artifacts associated with metal implants, the implant itself, the interface between implant and bone as well as the adjacent soft tissue may be misinterpreted, thus pathologies such as periprosthetic fractures, implant loosening, hematomas or signs of inflammation in the surrounding soft tissue may be missed.

Metal artifacts consist of photon starvation due to a complete absorption of the photons [4], beam hardening caused by the preferential absorption of low energy photons of the X-ray [5,6], and scatter artifacts caused by the high attenuation coefficients of metal implants [7,8].

In conventional CT, metal artifact reduction is commonly achieved by optimization of acquisition and reconstruction parameters using (a) a high peak voltage (kV_p), (b) an increased tube current × time product (mAs), (c) a narrow collimation, (d) greater slice thickness and (e) appropriate reconstruction filters [3]. Specific post-processing algorithms, which are provided by different vendors, are available to reduce metal artifacts even further [9–11].

Since the clinical introduction of spectral or dual-energy CT imaging [12], virtual monoenergetic images have become available and have emerged as a new means for metal artifact reduction [13–15]. In dual-energy CT, a high-energy and a low-energy dataset are acquired using polyenergetic X-ray spectra. Virtual monoenergetic images approximating datasets that would result from true monoenergetic image acquisition can be calculated as linear combinations of these two datasets [16]. This is possible across a broad range of energies (reported in kiloelectron-volts, keV), but has a lower limit above the iodine k-edge (33 keV) due to non-linear behavior [17,18]. Because of the higher attenuation of soft X-rays, low-energy virtual monoenergetic images result in higher low-contrast resolution and, in the presence of iodine

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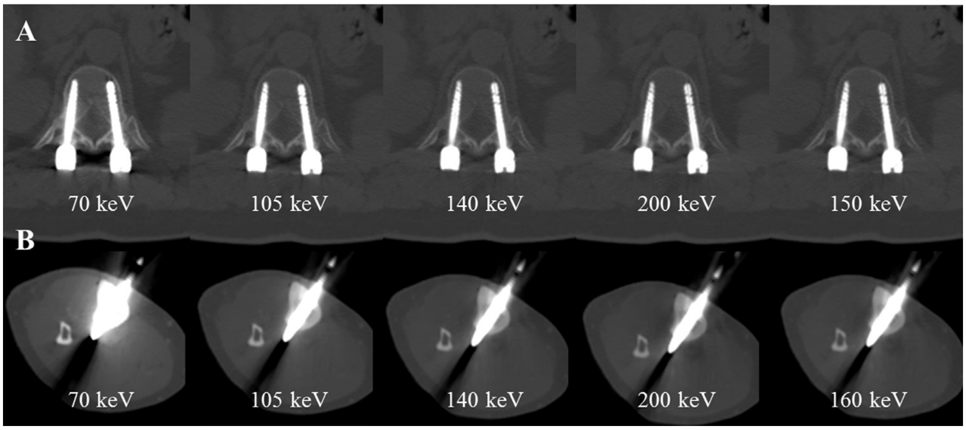

Fig. 1. Images showing pedicle screws in a thoracic vertebra (A) and a screw in the tibia (B) reconstructed at equivalent-keV, 105 keV, 140 keV, 200 keV and optimal keV.

contrast agent, in an improved iodine visualization for energies in proximity of the respective k-edge [19,20]. Hard X-rays on the other hand are less attenuated e.g. by dense materials, therefore it can be expected that the corresponding virtual monoenergetic images display less artifacts from metallic implants [16].

The high-energy and low-energy datasets for dual-energy CT imaging can be generated using different approaches either focused on X-ray tube output or on X-ray detection. Clinically implemented are currently four tube-based concepts with a high and a low mean energy X-ray spectrum obtained from: (a) two consecutive rotations at different tube potentials (dual-spin), (b) two independent orthogonally positioned tube-detector systems at different tube potentials (dual-source), (c) from splitting the output of a single X-ray source using a beam filter resulting in two partial beams with high and low mean energies (split or twin beam), and (d) from rapid switching of the tube potential of a single X-ray source during a single rotation (kV_p switching) [21]. The only commercially available detector-based solution (dual-layer) also uses a single X-ray source and measures the lower part of the spectrum in the surface layer whereas the photons of higher energies are detected in the layer below [18,21]. Unique to the dual-layer approach is the simultaneous measurement of low and high-energy projection data at the exact same spatial and angular location which allows for a raw-data based dual-energy post-processing superior to image-based methods, particularly with respect to beam-hardening correction which is relevant for metal artifact reduction [22]. For kV_p switching, raw-data post-processing is only possible after angular and temporal interpolation which deteriorates spatial and temporal resolution. The other tube-based approaches allow only for dual-energy post-processing in the image domain [23].

In this study we aimed to evaluate metal artifact reduction on virtual monoenergetic image datasets acquired with a novel dual-layer CT (DLCT) system using raw-data based dual-energy post-processing methods. The image quality of the virtual monoenergetic datasets was assessed in terms of quantitative density and width measurements as well as qualitative grading of artifacts.

2. Methods

2.1. Study population and study design

This study was performed according to the international quality standard of good clinical practice, the 2013 Declaration of Helsinki, and the German radiation protection ordinance, German X-ray ordinance, data protection act, and health data protection act of North Rhine-Westphalia, Germany. The presented study was approved by the local ethics committee (Registration number 16-292).

The study included the CT scans from a randomized subset of patients, who had been referred to the Department of Diagnostic and Interventional Radiology of the University Hospital Cologne in the time period from June to July 2016. CT scans have been requested with clinical indications and no CT scan was acquired explicitly for the purpose of this study.

All CT scans were performed using the dual-layer IQon® Spectral CT (Philips Healthcare, Amsterdam, The Netherlands). Inclusion criteria were: (a) CTs of the thorax, abdomen and extremities which contained orthopedic, metal implants, (b) reconstruction using a bone kernel (Philips Filter Sharp C), (c) slice thickness of 2 mm, (d) pitch of 1 and (e) dose application with tube current $>$ 100 mA and voltage 120 kVp.

2.2. Analysis of CT scans

Virtual monoenergetic images were viewed independently using the proprietary spectral viewer (Spectral Diagnostics Suite (SpDS), Philips, Amsterdam, NL) by three different observers (JB, RR, VN) with eight, six and three years of experience in interpretation of CT scans. For quantitative measurements representative images in the axial plane showing the metal implant were reviewed in the bone window (width 2000 HU, center 800 HU) at different photon energies. For qualitative analysis the observers could use the entire 3D data of the acquired CT, also viewing the images in the bone window and at different photon energies. Images at 64–70 keV served as reference for conventional CT images that were acquired with a tube voltage of 120 kVp. These photon energies are provided as default values by the post-processing software and are referred to as equivalent-keV, since they are the virtual monoenergetic images with the highest similarity of the CT numbers compared to the conventional images. The virtual monoenergetic images were reconstructed at energies of 105 keV, 140 keV, 200 keV and with an optimized keV, that was selected by the observer from a range of 40 keV to 200 keV (Fig. 1).

The quantitative measurements of the artifacts included a measurement of the density of the most pronounced, hypodense artifact (in Hounsfield units, HU). Therefore, a region of interest (ROI) was placed in the artifact close to the metal implant (Fig. 2). Additionally the standard deviation (SD) of the CT number within the ROI was measured. A reference measurement was conducted by placing a ROI in the soft tissue that was not or as little as possible affected by artifacts and presumably of same type of soft tissue as obscured by the artifact mentioned above (Fig. 2). Additionally the width of the most pronounced, hypodense artifact was measured close to the metal implant in its largest diameter (Fig. 2). ROIs were kept constant and measurements of width were conducted in the same location at all investigated kilo-electron volt levels.

Qualitative measurement of artifacts was committed using a five-point Likert scale, which graded the artifacts caused by the metal implants as absent (1), only at the thickest portion of the metal implant (2), minor (3), pronounced (4) and massive (5) [24].

The qualitative assessment of the diagnostic image quality, especially the assessment of bone and soft tissue adjacent to the investigated