Physica Medica 53 (2018) 4–16

Contents lists available at ScienceDirect

Physica Medica

journal homepage: www.elsevier.com/locate/ejmp

Original paper

Development of a novel algorithm for metal artifact reduction in digital tomosynthesis using projection-based dual-energy material decomposition for arthroplasty: A phantom study

Tsutomu Gomi*, Rina Sakai, Masami Goto, Hidetake Hara, Yusuke Watanabe

School of Allied Health Sciences, Kitasato University, Sagamihara, Kanagawa, Japan

ARTICLE INFO

Keywords:
Tomosynthesis
Dual-energy
Metal artifacts

ABSTRACT

In this study, a novel dual-energy (DE) material decomposition reconstruction algorithm (DEMDRA) was developed using projection data with the aim of reducing metal artifacts during digital tomosynthesis (DT) for implants. Using the three-material decomposition method and decomposition projection data specific for each material, a novel DEMDRA was implemented to reduce metal artifacts via weighted hybrid reconstructed images [maximum likelihood expectation maximization (MLEM) and shift-and-add (SAA)]. Pulsed X-ray exposures with rapid switching between low and high tube potential kVp were used for DE-DT imaging, and the images were compared using conventional filtered back projection (FBP), MLEM, the simultaneous algebraic reconstruction technique total variation (SART-TV), virtual monochromatic processing, and metal artifact reduction (MAR)-processing algorithms. The reductions in metal artifacts were compared using an artifact index (AI), Gumbel distribution of the largest variations, and the artifact spread functions (ASFs) for prosthesis phantom. The novel DEMDRA yielded an adequately effective overall performance in terms of the AI, and the resulting images yielded good results independently of the type of metal used in the prosthetic phantom, as well as good noise artifact removal, particularly at greater distances from metal objects. Furthermore, the DEMDRA represented the minimum in the model of largest variations. Regarding the ASF analysis, the novel DEMDRA yielded superior metal artifact reduction when compared with conventional reconstruction algorithms with and without MAR processing. Finally, the DEMDRA was particularly useful for reducing high-frequency artifacts.

1. Introduction

Cementless hip arthroplasty has become increasingly popular in clinical practice in recent years. The success of this procedure requires reliable biological fixation[1] , and imaging has become an important tool for evaluating the postoperative placement of hip arthroplasty components, as well as the possible long-term complications [2]. Digital tomosynthesis (DT) combines the benefits of digital imaging [1–9] and computed tomography to provide three-dimensional (3D) structural information and can easily be implemented together with radiography to reduce radiation doses and procedural costs. However, the process of DT image reconstruction is inconsistent and limited by low signal-to-noise ratios caused by the superposition of several low-exposure projection images.

Metal artifacts, which deteriorate image quality by reducing contrast and obscuring details, hinder the detection of structures of interest and may lead to misdiagnosis. For the imaging of cases involving metallic joint prostheses or osteosynthetic materials, metal implants and their interactions with radiation and surrounding tissues should be evaluated, and hematoma or inflammation in the adjacent soft tissue should be ruled out. However, evaluations of such cases are greatly impeded by metal artifacts, which frequently render the images uninterpretable using conventional image reconstruction. Particularly that filtered back projection (FBP) [5] is used even for datasets with hard convolution kernels (e.g., Ramachandran or Shepp–Logan filter kernels).

In DT, artifacts appear as areas of very low signal along the sweep direction around the edges of highly attenuating materials (e.g., metal prostheses or osteosynthetic materials) and are predominantly caused by mismatches between the assumptions of the reconstruction algorithm (i.e., ideal monochromatic beam) and reality (i.e., a wide spectral range). The limited sweep angle also contributes to this phenomenon, although the effect of this factor is relatively minor. Thus, other researcher have evaluated metal artifact reduction (MAR) on CT and

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* Corresponding author at: School of Allied Health Sciences, Kitasato University, Kitasato 1-15-1, Minami-ku, Sagamihara, Kanagawa 252-0373, Japan.
E-mail address: gomi@kitasato-u.ac.jp (T. Gomi).

https://doi.org/10.1016/j.ejmp.2018.07.011
Received 9 March 2018; Received in revised form 13 June 2018; Accepted 28 July 2018

DT[9–12] .

Previous studies of DT for arthroplasty have also explored iterative reconstruction (IR) [1,6,7,9]. Compared with the FBP technique, IR was found to provide superior image quality and a good balance between low- and high-frequency features [1,7,9]. Notably, several previous studies have quantitatively compared the image qualities and radiation doses produced by several existing DT algorithms for arthroplasty [7,13] and observed that IR effectively decreases both quantum noise and radiation exposure.

Recent developmental research efforts have yielded an iterative algorithm for volume image reconstruction from tomographic scans based on total variation (TV)-based compressive sensing [14–18]. The TV of an image, defined as the sum of the first-order derivative magnitudes for all pixels in the image, has been used as a penalty term in iterative image reconstruction algorithms [18]. In IR with TV minimization, an image domain optimization method associated with compressed sensing theory [16,18], the addition of a penalty to the data-fidelity-objective function tends to smooth noise while preserving the edges within an image [14–19]. Gomi and colleagues evaluated the effects of metal artifact reduction using existing reconstruction techniques, including TV-minimization reconstruction and a MAR processing algorithm, and concluded that TV-minimization reconstruction alone could not significantly improve metal artifact reduction when compared with the conventional algorithm [13]. The exclusion of any standard metal artifact correction techniques such as sinogram inpainting or an iterative method with a polychromatic model means it is hard to correction the relative merit of TV denoising algorithm for artifact suppression. These findings and current situations (limit of correction for metal artifacts using polychromatic imaging) these findings show the need for new reconstruction algorithm that other algorithms, and techniques, also successful in reducing metal artifacts even before DT.

Metal artifacts are generated by many physical factors, such as X-ray scattering, photon starvation, and beam hardening; the latter is caused by the passage of polychromatic X-ray photons through a medium. Researchers have previously proposed the use of dual-energy (DE) virtual monochromatic spectral imaging to reduce beam hardening metal artifacts [14–19]. Currently, the accuracy of material decomposition measurements is reduced by the presence of multiple tissue types, particularly in terms of differentiation and quantification. These difficulties are attributed to the relationship of the measured reconstructed voxel to the linear attenuation coefficient, which is not unique for any given material but is a function of the material composition, the interactions of photons with the material, and the mass density of the material. During DE acquisition, however, the material decomposition can be differentiated using an additional attenuation measurement obtained at a second energy. Therefore, DE material decomposition can be defined as the use of (1) attenuation measurements acquired with different energy spectra and (2) knowledge of the changes in attenuation between the two spectra in order to differentiate and classify tissue composition [20,21].

CT studies have previously reported using DE virtual monochromatic imaging (projection space approach and image space approach) to achieve metal artifact reduction [14–19]; specifically, metal artifact reduction was successfully achieved by reconstructing projection data decomposed using materials in projection space [15]. However, although a DE subtraction technique has been reported for DT in the chest imaging area [22,23], no previous report describes the application of two material decomposition (bone and soft tissue) to a DE technique. The DE two-material decomposition technique involves two types of weighted blending methods: low- and high-energy. Choosing the blending ratio for this technique is a trade-off between reduced noise and contrast information; thus, a shift in ratio in one direction will produce a blended image with less noise, but also less contrast information. Still, the combination of DE with ~~a~~ three material decomposition technique could potentially yield a high-level solution to inherent problems. Additionally, metal artifacts might be reduced by reconstruction using decomposed projection data from each material (e.g., titanium, bone) and blending image processing. In this study, we developed a new projection space approach-based hybrid method of reconstruction from DE material decomposition with the aim to reduce metal artifacts [DE material decomposition reconstruction algorithm (DEMDRA)] for DT. The developmental process and basic evaluation of the method are described in this report.

Table 1
Specification of prosthetic phantom used in this study.

Prosthetic phantom	Diameter (mm)	Overall length (mm)	Object & local density (g/cm^3)
[Artificial bone]			
Orthopedic Humerus Normal Anatomy (Model 1013, Sawbones, Inc., WA, USA)	9*	300	Foam cortical shell 0.48
[Implant]			
Proximal Retrograde Humeral Nail® (PRHN, Mizuho Inc., Tokyo, Japan)	7	100	Titanium alloy 4.43

* Canal diameter.

2. Materials and methods

2.1. Phantom specifications

To evaluate reductions in metal artifacts, we immersed a prosthetic phantom containing an artificial bone and implant (Table 1) in the center of a polymethyl methacrylate case filled with water (case dimensions, φ 200 × 300 mm). The prosthetic phantom contained a simulated humeral proximal fracture (internal fracture fixation via retrograde intramedullary nail fixation). This phantom was arranged parallel to the detector plane for DE-DT acquisition (Fig. 1).

2.2. DE-DT system

The DE-DT system (SonialVision Safire II; Shimadzu Co., Kyoto, Japan) comprised an X-ray tube (anode: tungsten with rhenium and molybdenum; real filter: inherent; aluminum [1.1 mm], additional; aluminum [0.9 mm] and copper [0.1 mm]) with a 0.4 mm focal spot and 362.88 × 362.88 mm amorphous selenium digital flat-panel detector (detector element, 150 × 150 μm^2). The source-to-isocenter and isocenter-to-detector distances were 924 and 1100 mm, respectively (anti-scatter grid, focused type; grid ratio, 12:1).

Collimator motion was synchronized by measuring the misalignment of the low- (70 kV) and high-kV (140 kV) images at a constant tube motion. A large energy gap between low and high tube potential kVp imaging yields better material decomposition [14–21]. We selected the above-mentioned kV values because this study aimed to improve metal artifact reduction during DT acquisition while maintaining an imaging performance similar to that of conventional DT.

Pulsed X-ray exposures and rapid switching between low and high tube potential kVp were used for DE-DT imaging. Linear system movement and a swing angle of 40° were used when performing tomography, and 37 low- and high-voltage projection images were sampled during a single tomographic pass. Although clinical applications (e.g., prosthesis assessment) usually use a low-voltage, each projection image was acquired at 187 mA and a 22 ms exposure time for low-voltage X-rays and at 260 mA and a 5 ms exposure time for high-voltage X-rays. To generate reconstructed tomograms of the desired height, we used a 1024 × 1024 matrix with 32 bits (single-precision floating number) per image (pixel size, 0.252 mm/pixel; reconstruction interval,