EVALUATION OF METAL ARTEFACT REDUCTION USING DUAL-STEP ADAPTIVE THRESHOLDING TECHNIQUE IN COMPUTED TOMOGRAPHY

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TABLE OF CONTENT

PAGE

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

CT	Computed tomography
DSAT	Dual-step adaptive thresholding
FBP	Filtered back-projection
HU	Hounsfield unit
kVp	Kilovoltage peak
MAC	Metal artefact correction
mAs	Milliamperage-seconds
PACS	Picture archiving and communication system
ROI	Region of interest
SD	Standard deviation
SNR	Signal-to-noise ratio

ABSTRAK

Objektif: Objek logam yang terdapat dalam imej imbasan tomografi berkomputer boleh menghasilkan artefak. Kewujudan artefak yang teruk akan menyebabkan kualiti imej merosot dan boleh mengaburi penemuan klinikal dan patologi yang penting di sekitar objek logam. Tujuan kajian ini adalah untuk mengkaji keberkesanan teknik *dual-step adaptive thresholding* (DSAT) dalam mengurangkan artefak logam yang terdapat dalam imej CT.

Metodologi: Sejumlah 14 pemeriksaan CT yang mengandungi artefak logam yang terhasil daripada pelbagai jenis implan pembedahan diambil dari Sistem Komunikasi Arkib Gambar (PACS). Imej-imej CT ini diproses menggunakan algoritma DSAT melalui perisian MATLAB untuk menghasilkan imej pembetulan bagi kesan artefak dengan kualiti yang baik. Kedua-dua kumpulan imej asal dan imej yang telah dibetulkan dinilai secara kuantitatif menggunakan nilai SD dan SNR dan secara kualitatif menggunakan penilaian visual oleh 2 orang penilai. Tahap kepentingan telah ditentukan ($p < 0.05$).

Keputusan: Pengurangan SD yang sangat ketara diperolehi selepas proses pembetulan artefak logam menggunakan teknik DSAT dengan purata 14.576 ± 11.7 untuk imej CT yang diproses berbanding dengan 40.177 ± 23.785 untuk imej asal ($p < 0.0005$). Terdapat peningkatan SNR yang signifikan selepas melalui proses pembetulan artefak dengan min 3.877 ± 3.931 untuk imej yang diproses berbanding 3.614 ± 2.839 untuk imej asal ($p = 0.017$). Penilaian visual menunjukkan terdapat pengurangan kesan artefak logam dan struktur bersebelahan implan kelihatan semakin jelas ($p < 0.05$).

Kesimpulan: Pembetulan artefak logam menggunakan teknik DSAT mampu mengurangkan kesan artifak logam dalam imej CT dan dapat meningkatkan kualiti imej dengan signifikan.

Kata kunci: *dual-step adaptive thresholding; metal artefact reduction; computed tomography; image segmentation*

ABSTRACT

Background: Metal objects present in CT images may give rise to streak artefact. In the presence of severe artefacts, image quality may be extensively degraded and important clinical findings and pathology in the vicinity of the metal objects may be obscured. The purpose of this study is to evaluate the effectiveness of the dual-step adaptive thresholding technique as a method of metal artefact reduction in CT studies.

Methodology: A total of 14 CT studies which contained metal-induced artefacts resulted from various surgical implants were retrieved from the Picture Archive Communication System (PACS). The CT images were corrected using the DSAT algorithm in MATLAB workspace to generate the artefact-corrected images with acceptable quality. Both groups of original images and artefact-corrected images were evaluated quantitatively using noise and SNR and qualitatively using visual evaluation by 2 evaluators. Level of significance was determined ($p < 0.05$).

Results: A significant reduction of the noise were noticed in the corrected CT images following DSAT technique for metal artefact correction with the mean noise of 14.576 ± 11.7 as compared to the original images with mean of 40.177 ± 23.785 ($p < 0.0005$). A significant improvement of SNR was also demonstrated following DSAT correction with the mean SNR of 3.877 ± 3.931 for the corrected images in comparison to 3.614 ± 2.839 for the original images ($p = 0.017$). Visual evaluation has demonstrated reduced appearance of metal artefacts with increased conspicuity of adjacent structures ($p < 0.05$).

Conclusion: Metal artefact correction using dual-step adaptive thresholding technique has the ability to suppress metal-induced artefacts with significant improvement of image quality.

Keywords: *dual-step adaptive thresholding; metal artefact reduction; computed tomography; image segmentation*

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

Computed tomography (CT) has become one of the important radiological examinations in recent years and has shown an incremental pattern of usage annually in most countries (Thomas, 2011). In the United States, the number had significantly increased from 3 million in the early 1980s to 67 million in 2006 whereas there was an average growth of 10.1% annually from 2003-2004 until 2013-2014 in England (Schauer and Linton, 2009; Svenson and Steele, 2014). In spite of no available data regarding the CT utilisation in Malaysia, the numbers of CT examination in other countries in Asia Pacific region have also shown pattern of upsurge (Sun and Ng, 2012). The number of CT services in Australia from 1994 until 2009 had more than tripled with average annual growth rate of 8.5% (Brady *et al.*, 2011). A hospital-based study was conducted in Taiwan to analyse the CT utilisation rate for emergency department visits which showed significant increase in utilisation rate from 11.10% in 2009 to 17.70% in 2013 (Hu *et al.*, 2016). The increase in the figures are mainly attributable to the fact that CT scan produces cross-sectional views of the body parts which helps in more definitive diagnosis with short acquisition time compared to other radiological examinations. Despite its growing importance and advancement in recent years, there are some limitations that could adversely affect the image quality and diagnosis, for instance, the presence of non-removable metal objects in patients.

CT examination involving patient with metal objects may give rise to streak artefacts in CT images. This type of CT artefact appears as dark and bright lines emanating from the metal objects. The appearance of metal artefacts are mainly due to the effects of: 1) beam hardening; when the x-ray photons pass through the metal object, the mean energy of the photons increases as the low-energy photons in the x-ray spectrum are absorbed causing the appearance of dark streaks; 2) scatter; the scattered photons cause more signal to be detected than expected, which also causes the dark and bright streaks; 3) photon starvation; as photons are strongly attenuated by large sized metal implants or metal with high atomic number, only a small number of photons reach the detectors, resulting in increase of the noise and incomplete projection which subsequently causes production of streaks along the direction of greatest attenuation (Barrett and Keat, 2004; Osman *et al.*, 2007; Yazdi and Beaulieu, 2007).

Knowledge of factors influencing the severity of metal artefacts are important in order to reduce the occurrence of the artefacts and to obtain excellent image quality. The severity of these artefacts depends on several factors including tube current (mA), x-ray kilovolt peak (kVp), reconstruction kernel, pitch, metal composition, the size and the shape of the metal objects (Douglas-Akinwande *et al.*, 2006; Osman *et al.*, 2007; Stradiotti *et al.*, 2009). Low x-ray energy causes poor beam penetration through the metal object and thus increases the metal artefacts. High pitch setting contributes to increased metal artefacts due to fewer projection data collection. Smooth reconstruction kernel, high density metal and object with large size and complex geometry are all known contributing factors to increased appearance and severity of the metal artefacts.

In the presence of severe artefacts, image quality may be extensively degraded and important clinical findings and pathology in the vicinity of the metal objects may be obscured and this may lead to misdiagnosis. Examples include orthopaedic implants in the presence of pathological fractures, hip prostheses in patients with pelvic diseases, dental fillings in patients with oral lesion and the presence of aneurysmal clips and coils during assessment of intracranial pathology.

Most of the orthopaedic instrumentations are made up of materials such as cobalt-chrome, stainless steel, and titanium alloy. CT imaging is the modality of choice for the post-operative assessment as the application of the magnetic resonance imaging (MRI) is limited since it allows only non-ferromagnetic materials to be imaged. However, the presence of severe streak artefacts in CT images impairs the post-operative assessment of spinal fusion or fracture fixation and may render the efficacy of CT imaging in the patient management.

Many studies on CT metal artefacts have been conducted in the past several years and different scanning techniques and post-processing algorithm been proposed to reduce the metal artefacts in CT images. These studies were described further in the literature review. Many of the proposed metal artefact reduction (MAR) techniques are based on single step thresholding (Bazalova *et al.*, 2007; Chen *et al.*, 2012; Yazdi *et al.*, 2005) which use a single threshold value of Hounsfield Unit (HU) to identify the metal-containing voxels and subsequently segments the metal region in the original image. However, most of the proposed MAR algorithms are not suitable in clinical routine mainly because of the high computation time, introduction of new artefacts and loss of detail surrounding the metal-tissue interface (Barrett and Keat, 2004; Osman *et al.*, 2014; Yu *et al.*, 2009). New generation CT scanners are equipped with MAR software. However, they are not widely affordable due to the high cost.

Dual-step adaptive thresholding (DSAT) is a new modified thresholding technique developed by Osman *et al.* (2014) which involves the segmentation of the original sinogram twice for a more accurate correction. This technique works on virtual sinogram which is produced through forward projection of the original CT images in MATLAB workspace. It was reported that the technique showed significant improvement in image quality post metal artefact correction with preservation of anatomical details adjacent to the metal objects (Osman *et al.*, 2014). However, the previous study was mainly done using phantom and limited number of clinical CT images. The assessment of the image quality was also limited through measurement of noise and signal-to-noise ratio (SNR) without visual evaluation.

Therefore, the purpose of this study was to evaluate the effectiveness of the dual-step adaptive thresholding technique for metal artefact reduction using the CT studies of real patients. The performance of this algorithm was evaluated using noise and signal-to-noise ratio (SNR) measurement and visual assessment of the metal artefacts.

1.2 OBJECTIVES

1.2.1 General Objectives

To study the effectiveness of the dual-step adaptive thresholding technique for metal artefact reduction in CT studies.

1.2.2 Specific objectives

1. To compare the noise and signal-to-noise ratio (SNR) between the original images and the corrected CT images.

2. To compare the appearance of metal artefacts between the original images and the corrected CT images.

3. To compare the visual conspicuity of adjacent structures between the original images and the corrected CT images.

CHAPTER 2: LITERATURE REVIEW

METAL ARTEFACT REDUCTION (MAR) TECHNIQUES

Many studies have been conducted in the past several years on CT metal artefacts. Different scanning techniques and post-processing algorithms have been proposed to reduce the metal artefacts in CT images. The simplest methods include modification of image acquisition and reconstruction (Barrett and Keat, 2004; Kataoka *et al.*, 2010; Stradiotti *et al.*, 2009). Increasing the x-ray tube potential (kVp) results in higher x-ray energy and more beam penetration. This subsequently reduces the noise, beam hardening and photon starvation artefacts. Increasing the tube current (mAs) setting results in increased production of x-rays photons, less noise production and reducing the effect of photon starvation. Using lower pitch setting allows adequate collection of projection data, improves signal-to-noise ratio (SNR) and thus has cumulative effects in reducing metal artefacts (Osman *et al.*, 2007; Stradiotti *et al.*, 2009). However, increased radiation dose to the patient is the main limitation to these methods.

Gantry angulation technique has also been practiced to reduce streak artefacts by excluding the metal objects such as dental implants and filling during the process of scanning by modification of table position. Even though this technique is able to diminish the streak artefacts in adjacent slice, the inplane artefacts which are present within a slice cannot be effectively reduced (Tohnak *et al.*, 2011). This technique is also not widely used in clinical practice due to its only application in oropharyngeal cases.

Link *et al.* (2000) and Coolens and Childs (2003) proposed the use of extended CT-scale technique. Using this technique, the Hounsfield scale is expanded from a standard maximum greyscale window of 4072 HU to more than 40000 HU. It was reported that the visualisation of the metal implants were more enhanced (Link *et al.*, 2000). However, this technique causes lower contrast resolution of the tissue and is not much applicable in clinical routine.

In the last few years, many MAR techniques using post-processing mathematical algorithms on the artefactual images have been developed. In general, the correction techniques can be categorised into sinogram completion, iterative reconstruction and adaptive filtering approaches.

In sinogram completion, the correction technique is applied to raw projection data known as sinogram space. A sinogram is basically the 2D array of data containing all the projections of a single point and is represented as parallel beam. The sinogram shows the sinusoidal patterns due to simultaneous rotation of the x-ray source and detector around the object. The projection data can be obtained either directly from the CT scanner as implemented by Yazdi and Beaulieu (2006) or through the simulation of the sinogram. The major problem associated with the former approach is the difficulty in handling the large raw data files which require large computational memory. The later approach uses virtual sinogram which is produced through forward projection of the original CT images in MATLAB workspace as done by Abdoli *et al.* (2009).

In sinogram completion technique, the affected data corresponding to the projection through the metal objects are defined as missing data and are substituted by synthetic data before image reconstruction. Some methods are used to replace the missing data including linear interpolation (Mahnken *et al.*, 2003) and cubic interpolation (Bazalova *et al.*, 2007). Metal detection using threshold-based metal segmentation was developed by Mahnken *et al.* (2003) to avoid misinterpretation of the streak artefacts as real object or vice versa. In this technique, the missing projection is interpolated by the sum of weighted nearest projection values which are not affected by the artefacts. Even though the replacement values are taken from the unaffected projections in all directions, there is no continuity of the projections resulting in high noise production (Yazdi and Beaulieu, 2007). The previously discussed MAR approaches use filtered back-projection (FBP) for the image reconstruction after the projection interpolation.

Another approach used in MAR techniques for the interpolation of the missing projections is through iterative reconstruction. Metal deletion technique (MDT) was an improved iterative method developed by Boas and Fleischmann (2011). It uses the high quality non-metal data for iterative reconstruction and discards the projection data near the metal objects which are less accurate. They reported that the method resulted in better image quality compared to FBP. However, the iterative-based techniques has slow computational speed and long computational time which makes these techniques impractical for daily clinical use (Chen *et al.*, 2012; Yazdi and Beaulieu, 2006).

Adaptive filtering algorithms are another method used in metal artefact correction. The application of smoothing filter is done adaptively on the projection data according to the noise level before the reconstruction. The filter can be adjusted to adapt to the surrounding noise. More recent modified application of this method was proposed by Chen *et al.* (2012). This algorithm uses large-scale non local means (LS-NLM) filter on the original image to reduce the noise prior to metal segmentation.

Many limitations are found in the proposed MAR methods including partial reduction of metal artefacts, introduction of secondary artefacts in the corrected images and formation of blurred images (Osman *et al.*, 2014). These MAR techniques are also mostly based on single thresholding to detect the metal elements in the original images (Bazalova *et al.*, 2007; Chen *et al.*, 2012; Yazdi and Beaulieu, 2006; Yazdi *et al.*, 2005). This method uses a single threshold value of Hounsfield Unit (HU) to identify the metal-containing voxels and subsequently segments the metal region in the original image. The shortcoming of using this single step thresholding technique is that there is detail loss in the region adjacent to the metal object after correction which renders the efficacy of this technique (Barrett and Keat, 2004; Osman *et al.*, 2014).

Dual-step adaptive thresholding (DSAT) is a new modified thresholding technique developed by Osman *et al.* (2014) which involves the segmentation of the original sinogram twice for more accurate correction. This technique is based on sinogram completion. It works on virtual sinogram which is produced through forward projection of the original CT images in MATLAB workspace based on work done by Abdoli *et al.* (2009).

The first thresholding step uses very high threshold value, T_{metal} to identify metal-only regions. These regions are then segmented from the original sinogram to create a sinogram without metal trace. This is to identify the corrupted data in the region affected by the metal artefact and is important for the later interpolation step. In the next thresholding step, high-density regions which include the metal and bony parts are identified and segmented using a lower threshold value, T_{bone} to create a subset of metal-bone sinogram. The advantage of this step which is not present in other single thresholding MAR methods is the ability to preserve the anatomical details located nearby the metal object.

The next step in this MAR technique is to interpolate and replace the missing data pertaining to the metal trace. This step is based on cubic spline interpolation which basically replaces the data with appropriate artificial values using 4-point neighbouring data to produce the interpolated sinogram. The following step involves image reconstruction and enhancement to produce better image quality. The reconstruction of the interpolated image and bone-metal image is based on filtered back-projection (FBP). Spatial filtering techniques are applied onto the reconstructed images to enhance the quality of the images. These filtered images are finally fused together to generate the corrected CT images.

It was reported that the DSAT technique showed significant improvement in image quality post metal artefact correction with preservation of anatomical details adjacent to the metal objects (Osman *et al.*, 2014). This is a major advantage of this technique compared to the other MAR techniques using single thresholding. However, the previous study conducted by Osman *et al.* (2014) mainly worked on phantom and limited number of clinical images of real patients. The assessment of the image quality was limited through measurement of noise and signal-to-noise ratio (SNR) without visual evaluation.

Therefore, the purpose of this study was to evaluate the effectiveness of the DSAT technique for metal artefact reduction using CT studies of real patients. The performance of this algorithm was evaluated using noise and signal-to-noise ratio (SNR) measurement and visual assessment of the metal artefacts.

CHAPTER 3: METHODOLOGY

3.1 STUDY DESIGN

This work was a retrospective study, which was conducted in the Department of Radiology, Hospital Universiti Sains Malaysia (HUSM).

3.2 POPULATION AND SAMPLE

CT images that were archived into PACS in the Department of Radiology, HUSM.

3.2.1 Sampling Method

The sampling method used in this study was simple random sampling. The samples were obtained through searching the CT examinations in the PACS according to random dates.

3.2.2 Inclusion Criteria

1. Patient with surgical implants, clippings or metal foreign bodies.
2. Images using smooth reconstruction kernel.

3.2.3 Exclusion Criteria

Metal implant with complex shapes.

3.3 SAMPLE SIZE CALCULATION

For objective 1:

Power and Sample Size Calculation (version 3.1.2, 2014) from website: http://biostat.mc.vanderbilt.edu/wiki/Main/PowerSampleSize was used to calculate the sample size using two paired means.

Based on the previous study conducted by Osman *et al.* (2014), the mean difference of the measured noise was 13.46 and the standard deviation (σ) was 77.61. Using the power of study (1-β) of 80% and significance level (α) of 0.05, total regions of interest (ROI) required per group was 263.

Based on the same study, the mean difference of the SNR was 0.611 and the standard deviation (σ) was 8.16. Using the power of study (1-β) of 80% and significance level (α) of 0.05, total regions of interest (ROI) required per group was 1400.

Therefore, the larger number of ROIs which is 1400 was used. A total of 14 CT studies (10 to 20 slices per study) with the average of 100 ROIs per CT study were required to produce a total of 1400 ROIs.

For objective 2:

No previous literature was found with identical scoring system. Therefore, sample size will be based on objective 1.

For objective 3:

No previous literature was found with identical scoring system. Therefore, sample size will be based on objective 1.

3.4 MATERIALS AND METHOD

3.4.1 Research Tools

1. CT scanner machine - Siemens SOMATOM Definition AS+ CT Scanner (Siemens Healthcare, Germany).
2. DSAT metal artefact correction algorithm developed in MATLAB workspace.
3. MATLAB software (version R2009a).
4. PACS system – GE Centricity Universal Viewer.
5. RadiAnt DICOM Viewer (version 3.4.2).
6. OsiriX 9.0 viewer.
7. IBM SPSS Statistics (version 24).

3.4.2 Imaging protocols

The standard x-ray tube potential was used which is 120 kVp. Different mAs settings were used and the values were automatically selected depending on the body regions with automatic exposure control (AEC) setting.

3.4.3 Operational definition

1. Signal - Signal in CT imaging is proportional to the X-ray photon absorbed and detected by the CT detector. It is defined as the mean attenuation value and expressed as mean Hounsfield unit (HU) within the region of interest.

2. Noise - Noise refers to the statistical fluctuation in CT numbers within ROI in a homogenous background. Quantum mottle contributes the most significant source of noise in CT imaging. Noise is defined as the standard deviation (SD) of the mean attenuation value within the ROI.

3. SNR - is calculated from the ratio of mean HU and noise and is defined as SNR = mean HU/image noise.

3.4.4 Data collection

CT images were selected from the PACS at the Department of Radiology, HUSM and were screened against the inclusion and exclusion criteria. The selected CT images which were the original images with metal artefacts were processed using the dual-step adaptive thresholding algorithm in MATLAB workspace (MATLAB R2009a software) to generate the corrected CT images.

3.4.5 Image analysis

1. Quantitative analysis between the original images and the corrected images was performed to obtain the noise and SNR values within the ROI. The measurement was made using RadiAnt DICOM Viewer (version 3.4.2).

2. Circular ROIs sized $0.1cm^2$ were drawn in various locations within the visually homogeneous areas which were affected by the metal artefacts. The ROIs were made at the same position for the corresponding slices of both original and corrected images of the same CT study.

3. Review of the original images and corrected images was performed by one radiologist and one radiology registrar to evaluate the appearance of metal artefacts and visual conspicuity of adjacent structures using subjective scoring.

4. The evaluation of the appearance of metal artefacts was based on 4-point scale as below:

   0 – very prominent artefacts;

   1 – artefacts are present but less prominent;

   2 – faint artefacts;

   3 – no artefacts.

5. The evaluation of visual conspicuity of the adjacent structures was also based on 4-point scale, as described below:

   0 – totally obscured, no structures identifiable or questionable recognition;

   1 – faint anatomic recognition;

2 – anatomic recognition with low confidence in a potential diagnosis;

3 – anatomic recognition with high confidence in a potential diagnosis.

6. The image review by the evaluators was performed separately and in one session for each evaluator. The images were rated independently by the evaluators.

7. The evaluators were blinded to the information of the CT examination including the status of the images (original or metal artefact corrected images).

8. The review was performed using OsiriX (version 9.0). Ten slices per CT study with a total of 28 CT studies (14 studies for original images and 14 studies for corrected images) were provided. The studies were sorted randomly and unpaired during the session. All images were viewed using bone setting with the window width of 1500 and the window level of 300. The evaluators were allowed to scroll through the slices and to zoom the images.

3.5 STATISTICAL ANALYSIS

Paired-samples t-test was applied to compare the noise and SNR of both original and DSAT-corrected CT images. Wilcoxon signed-rank test was used to compare the scores for the appearance of metal artefacts and the scores for the visual conspicuity of adjacent structures between the two CT image groups. Inter-rater agreement was tested using weighted Cohen's kappa. Significance value was set at $\alpha = 0.05$. All statistical analyses were performed using IBM SPSS Statistics (version 24). Appendix A summarises the flowchart of this study.

3.6 CONFIDENTIALITY AND PRIVACY

The subject's information was collected in the data sheet and labelled with serial number in order to maintain privacy and confidentiality of the subjects (Appendix B). No identifiable data were expressed and shared in to public. Neither the name nor any identifying information was used in any publication or press.

3.7 ETHICAL CONSIDERATION

This study was approved by Human Research Ethics Committee of Universiti Sains Malaysia Research Ethics Committee of Universiti Sains Malaysia (JEPeM code: USM/JEPeM/16020045), which complies with the Declaration of Helsinki (Appendix C).

CHAPTER 4: MANUSCRIPT

EVALUATION OF METAL ARTEFACT REDUCTION USING DUAL-STEP ADAPTIVE THRESHOLDING TECHNIQUE IN COMPUTED TOMOGRAPHY

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