DUAL-THRESHOLDING BASED SINOGRAM INTERPOLATION TO REDUCE METAL ARTEFACT IN COMPUTED TOMOGRAPHY IMAGING

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by

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LIST OF ABBREVIATIONS

AI	Artefact index
AMDI	Advanced medical and dental institute
ART	Algebraic reconstruction technique
BP	Backprojection
CS	Cubic spline
CT	Computed tomography
DICOM	Digital imaging and communication in medicine
DSAT	Dual-step adaptive thresholding
EM	Expectation maximization
FBP	Filtered back projection
HU	Hounsfield unit
HUSM	Hospital Universiti Sains Malaysia
IPC	Projections by contouring
IR	Iterative reconstruction
LI	Linear interpolation
LS-NLM	Large scale non-local means
MAR	Metal artefacts reduction
MATLAB	Matrix laboratory
MDT	Metal deletion technique
MDT	Metal deletion technique
MIMS	Mutual information maximized segmentation
MPR	Metal projection region
NFFT	Non-equispaced Fast Fourier Transforms
NMAR	Normalized metal artefact reduction

NPLV	Non-partial linear volume
PACS	Picture archiving and communication system
ROI	Region of interest
SD	Standard deviation
SI	Sinogram interpolation
SNR	Signal to noise ratio
TV	Total variation
USM	Universiti Sains Malaysia
λ-MLEM	Weighted maximum likelihood expectation maximization algorithm

LIST OF SYMBOLS

kVp	Peak kiloVoltage
mAs	Miliampere-second

PENENTUDALAMAN SINOGRAM BERASASKAN DWI-PENGAMBANGAN UNTUK MENGURANGKAN ARTIFAK LOGAM DALAM PENGIMEJAN TOMOGRAFI BERKOMPUTER

ABSTRAK

Artifak logam dapat merendahkan kualiti imej di dalam pengimejan CT dan menyebabkan berlakunya kesukaran dan kegagalan di dalam analisis diagnostik. Artifak logam muncul sebagai jaluran yang terang dan gelap di sekeliling objek metal. Ianya berlaku disebabkan oleh efek pengerasan pancaran, kekurangan photon, separa volum tidak linear, serakan photon dan juga algoritma pembetulan pengurangan artifak logam yang tidak sesuai. Tujuan bagi kajian ini adalah untuk menambahbaik teknik interpolasi sinogram untuk mengurangkan artifak logam di dalam imej CT. Prosedur kajian ini dijalankan menggunakan MATLAB. Langkah pertama prosedur kajian ini adalah pemerolehan sinogram virtual menggunakan transformasi Radon. Kemudian, bahagian metal di imej CT dikesan dan diasingkan dengan menggunakan teknik threshold. Dua teknik interpolasi iaitu interpolasi 'cubic spline (CS)' dan interpolasi 'Laplace (LI)' digunakan untuk mengisi bahagian sinogram yang kosong. Sinogram yg telah diinterpolasi dibina semula menggunakan unjuran terbalik dan kemudian imej yang telah terinpolasi dan imej metal digabungkan bagi menghasilkan imej terakhir. Sejumlah tujuh imej fantom dan enam imej klinikal yang mempunyai keterukan artifak berbeza dipilih untuk pembetulan MAR. Penilaian secara kualitatif dan kuantitatif dilakukan untuk menilai keberkesan teknik MAR ini. Hasil penemuan menunjukkan artifak logam nyata sekali dikurangkan oleh teknik LI (nilai-p = 0.02) berbanding teknik CS (nilai-p = 0.17).

Daripada analisis kuantitatif, indeks artifak (AI) untuk imej pembetulan-LI adalah rendah (AI purata = 66.07), tetapi imej pembetulan-CS menunjukkan nilai AI yang lebih tinggi (AI purata = 141.35) berbanding imej asal (AI purata = 99.31). Keputusan dari analisis kualitatif menunjukkan imej pembetulan-LI mendapat skor lebih tinggi (skor purata ± SD iaitu 1.75 ± 1.22) daripada pakar radiologi berbanding imej asal (1.08 ± 1.08) dan imej pembetulan-CS (1.33 ± 1.23). Kesimpulannya, teknik LI adalah lebih berkesan dan efektif untuk membetulkan artifak pada kedua-dua imej fantom dan klinikal yang mempunyai tahap keterukan artifak yang berbeza.

DUAL-TRESHOLDING BASED SINOGRAM INTERPOLATION TO REDUCE METAL ARTEFACT IN COMPUTED TOMOGRAPHY IMAGING

ABSTRACT

Metal artefacts can degrade the image quality of computed tomography (CT) images which lead to difficulties and errors in diagnostic analysis. Metal artefacts appear as bright and dark streaks around the metal object. It is caused by beam hardening effects, photons starvation, non-linear partial volume, photon scatter, undersampling and inappropriate correction algorithm during reconstruction of image. The aim of this study is to improve the sinogram interpolation technique for metal artefacts reduction (MAR) in CT images. The MAR algorithm of this study was developed using MATLAB platform. The first step of the algorithm was the acquisition of virtual sinogram from the CT image using Radon transform function. Then, the thresholding technique is used to detect and isolate the metal part within the sinogram of the CT image. Two interpolation methods, cubic spline (CS) and Laplace interpolation (LI) were applied to replace the missing sinogram data. The interpolated sinogram was then reconstructed using backprojection (by inverse Radon function) and finally the thresholded and interpolated images were fused to produce corrected image. A total of seven phantom and six clinical CT images with different artefacts severity were selected for MAR correction. Qualitative and quantitative evaluation of the corrected CT images was performed to evaluate the effectiveness of the proposed MAR technique. The findings showed metal artefact was significantly reduced by LI method (p-value = 0.02) as compared to CS method (p-value = 0.17). From quantitative analysis, the artefact index (AI) for LI-corrected images is lower (mean AI = 66.07), but CS-corrected images yielded higher AI values (mean AI = 141.35) than the original images (mean AI = 99.31). The results from qualitative analysis showed LI-corrected images received higher scores (mean score ± SD of 1.75 ± 1.22) from radiologist compared to original image (1.08 ± 1.08) and CS-corrected images (1.33 ± 1.23). In conclusion, LI method work more effectively in artefact reduction on both phantom and clinical images of different degrees of artefact severity.

CHAPTER 1

INTRODUCTION

This chapter briefly discussed the background of the whole study. It includes the problems that lead to the execution of this study and the overview of how the work was developed and carried out. It also includes the objective of this study to overcome the problems and gap of the current works. The scope and limitations of this study were also described in this chapter.

1.1 Background of the study

Many studies have been done to improve the image quality of computed tomography (CT) since CT scan was first introduced. One of the main causes that can degrade the image quality of CT imaging is artefacts. The presence of metal objects or implants such as screws, dental filling and rods can cause metal-induced artefacts that appear as streaks or dark areas around the metal object. It can also obscure the anatomical details around the metal objects on the CT image.

Several approaches have been done to reduce the appearance of metal artefacts. The simplest method is by discarding metal objects from the field of view during scanning. This method is only applicable for removable metal objects. For irremovable metal objects, options such as modification of the exposure setting by using higher tube current and tube voltage to increase the penetration are more likely to be used. But these options give drawback as it can increase radiation dose to patient. Positioning the scan plane at the area without metal implant can also reduce metal artefact but it might not be fully useful in certain cases.

The more efficient method is by alteration of the reconstruction algorithm known as metal artefact reduction (MAR) algorithm. This method can be categorized into two groups which are sinogram interpolation (SI) and iterative reconstruction (IR). The difference between these two methods is the technique used to reconstruct into the image which is either by filtered backprojection (FBP) or iterative reconstruction.

SI method consists of three main stages which are sinogram thresholding, interpolation and reconstruction process. This method is implemented by first segmenting the corrupted data within sinogram and then interpolating the missing data (segmented data) using new data points. The final step is reconstruction of the interpolated sinogram using FBP. This technique has been explored by few researchers for reduction of metal artefacts in CT imaging (Glover et al., 1981; Kalender et al., 1987; Duan et al., 2008; Abdoli et al., 2010; Meyer et al., 2010,2012; Lell et al., 2013).

The second group of the correction method is iterative reconstruction (IR). IR is mainly made up of three main steps. The first step is the forward projection of original image to create artificial raw data which then used to be compared with the real measured raw data. The correction data is then computed and backprojected. The process uses multiple repetitions and will be stopped when the ideal result is produced. Few studies have proved the effectiveness of this method for metal artefacts correction (Wang et al.,1996; Boas & Fleischann.,2011; Mehranian et al., 2011).

In this study, sinogram interpolation (SI) method was used as it is faster and computationally inexpensive. The same correction technique proposed by Osman et.al. (2014) will be employed. The drawback of this technique is the missing data was not fully interpolated, thus this study will further focus on improving the sinogram interpolation part in order to reduce the metal artefacts. The first step is generating a virtual sinogram from CT images. In the next step, the area of metal region in the sinogram will be detected and removed by thresholding method. Then the missing data will be replaced by new data points by the proposed interpolation method. Finally, the image will be reconstructed and evaluated to determine the effectiveness of the proposed method.

1.2 Problem statement

Metal artefact which originated from the metal object in the body such as metal implants, and dental fillings has been one of the problems in CT imaging. It is because metal artefacts can degrade image quality and anatomic visualization which lead to problem in diagnostic analysis. In addition, the current CT scanners which equipped with image processing software for metal artefacts correction are computationally expensive and some of it requires additional CT protocol.

Metal objects will absorb most of the x-ray photons and cause corrupted or missing projection data on the CT detector. As these missing or incomplete data are processed for image reconstruction, it will produce streaking artefacts on the reconstructed CT image (Abdoli et al., 2012). In diagnostic radiology, the presence of this artefact will impact and reduce the image quality and lead to misdiagnosis (Eslam and Abdelaziz, 2020; Zhou et al., 2018; Hu et al., 2017). This resulted errors in CT number, and it can cause inaccuracy in CT attenuation in hybrid imaging such as PET/CT imaging and radiation therapy treatment planning.

Few image processing methods known as metal artefact reduction (MAR) algorithm have been proposed to remove and reduce the appearance of metal artefacts. Most of the proposed MAR algorithm are projection-based correction (Katsura et al., 2018) using sinogram interpolation such as polynomial, linear and spline interpolation (Glover et al., 1981; Seitz & Rüegsegger., 1985; Kalender et al., 1987; Zhou et. al., 2000; Bruyant et. al., 2000; Meyer et al., 2010; Osman et.al., 2014). However, most of these proposed methods produced few drawbacks such as introduction of new artefacts and loss of anatomical information in the corrected CT images. Some of the proposed MAR methods also required specific CT protocol and involved very complex techniques, hence causing slow computational time. Several MAR algorithms have also been introduced by CT vendors (Eslam and Abdelaziz, 2020), but it is not affordable by most of the imaging centres.

The limitations of the previous work on the SI techniques (Osman et al., 2014) are incomplete interpolation due to the presence of severe artefacts with multiple metal implants, metal implants of complex shapes, and anatomical structures of complicated shapes and multiple densities. During the interpolation process, the missing data within the sinogram were not fully replaced or interpolated, as described in Figure 1.1. It will also cause loss of important anatomical information near the metal implant and also produced new artefacts on the final corrected images. Besides, most of the existing SI method also required long computational time and need large computational power which is not efficient for clinical implementation.

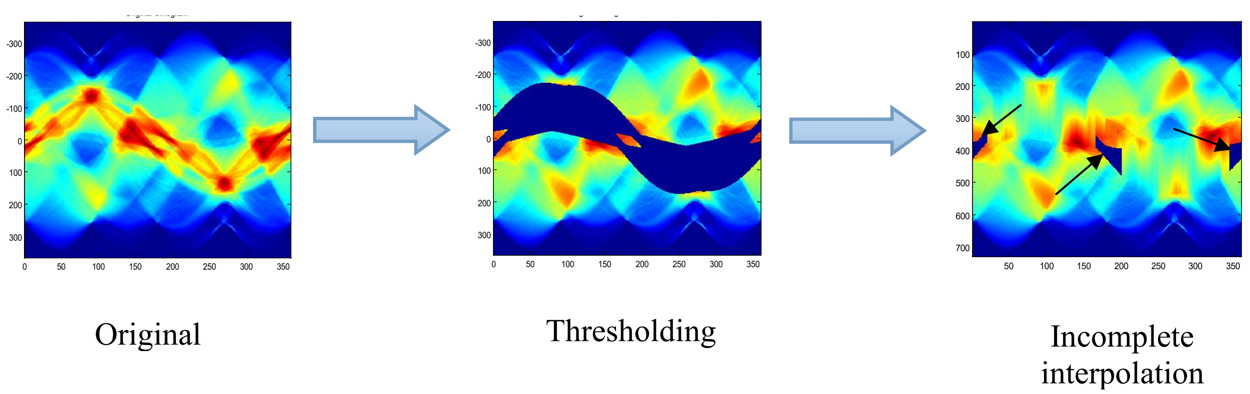

Figure 1.1 Incomplete interpolation process (right) of the missing data within the thresholded sinogram (middle) during the MAR technique

1.3 Objective of the study

1.3.1 General objectives

This study aims to improve the sinogram interpolation (SI) technique for metal artefacts reduction in CT imaging.

1.3.2 Specific objectives

1. To compare the different sinogram interpolation methods (cubic spline and Laplace interpolation) for metal artefacts reduction.
2. To select the best SI method in reduction of the missing data problem prior to sinogram interpolation of CT images.
3. To evaluate the efficiency of the proposed method in both phantom and clinical CT images by qualitative analysis through blinded scoring and quantitative analysis using signal-to-noise ratio (SNR) and artefact index (AI) evaluations.

1.4 Significance of the study

Metal artefacts reduction technique is an important technique to produce high quality images with acceptable diagnostic value. Various studies have been done to reduce metal artefacts on CT images and one the most efficient technique is by projection completion which includes synthesizing projection data to complete the sinogram. This study focuses on enhancing sinogram interpolation method that will be used to generate and replace the missing or corrupted projection data.

This study contributes a lot of advantages especially in clinical practices. The large computational time and power for processing the huge CT raw data can be solved by this method. It is because the virtual sinogram will be computed directly from the CT images, hence the system will be less time consuming and more efficient for clinical practice. The interpolation technique will also be improved in this study so that it can keep most of the anatomical information from the original image. Moreover, in this study, the images will be maintained in DICOM format throughout the image correction process. Therefore, the problem of losing the anatomical information will be reduced and the corrected CT images can be further used for clinical diagnosis within the DICOM viewer environment.

1.5 Scope and Limitations

This study is focusing on improving the previous sinogram interpolation (SI)-based algorithm and evaluating the best sinogram interpolation method for metal artefacts reduction in CT images. Phantom and clinical CT images obtained from Advanced Medical and Dental Institute (AMDI), USM and Hospital Universiti Sains Malaysia (HUSM) were collected and used independently. All phantoms and clinical CT images were only obtained from Siemens SOMATOM Definition AS+ CT scanners at both centres. Two types of sinogram interpolation were used and evaluated, which were cubic spline (CS) interpolation and Laplace interpolation (LI). The evaluation of the proposed MAR method was done qualitatively and quantitatively to measure the effectiveness of each interpolation method.

The limitation of this study is clinical CT images acquired from AMDI and HUSM have different bit depth stored. This has caused error to load the images onto the MATLAB platform for further analysis. Besides, the clinical CT images collected from both centres were also limited due to problem in obtaining the similar bit depth stored in each clinical images.

CHAPTER 2

LITERATURE REVIEW

This chapter provides a detailed review on previous published works related to metal-induced artefacts and methods for metal artefacts reduction in CT imaging. This chapter also described the fundamental knowledge related to this study along with previous MAR techniques proposed by other authors and their study outcomes. The literature review serves as a guide in development of the study design.

2.1 Metal Induced Artefacts

Artefact is defined as any systematic discrepancy between CT number in the reconstructed image and the true attenuation of the object (Barrett & Keat, 2004). In the presence of metal objects or implants such as screws, dental fillings and rods can cause metal artefacts which can degrade the image quality of computed tomography (CT) imaging (Zhang & Wan., 2017). Metal-induced artefacts appear as bright and dark streaks on the CT images, as shown in Figure 2.1 There are a few factors that contributes to the presence of metal or streak artefacts in CT imaging. They are mainly due to beam hardening, photon starvation, scatter, non-linear partial volume (NPLV) effect and undersampling (Katsura et al., 2018; Gjesteby et al., 2016).

X-ray photons interact differently to different absorbing materials based on their unique properties. These interactions or also known as x-ray attenuation is depending upon the energy of x-ray beam, atomic number of the materials, thickness of materials and density of the materials. In diagnostic range, x–ray attenuation occurs mainly due to photoelectric absorption and Compton scattering.

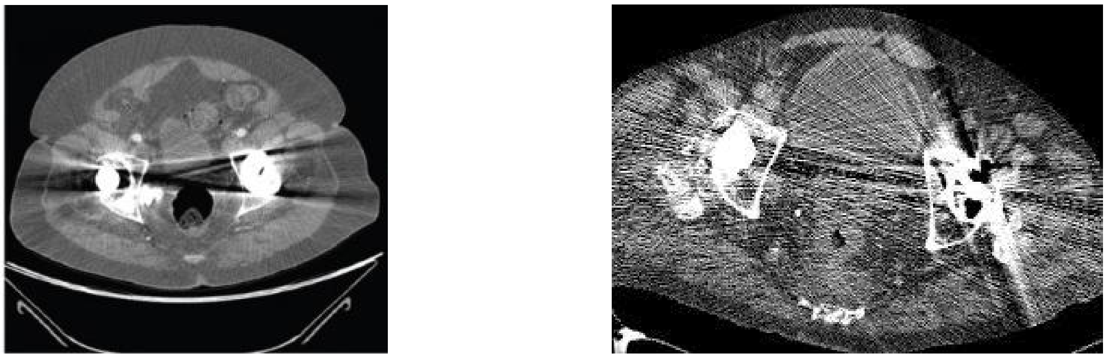

Figure 2.1 Examples of metal-induced artefact in CT images due to hip prosthesis

In Compton scattering, the x-ray photon strikes the outer shell of electron and ejecting it from its orbit. The electron is deflected in different direction with lower energy. Compton scattering is independent of atomic of materials and slightly dependent on the x-ray energy. While, in photoelectric absorption, the x-ray ejects electron from the inner shell of the atom. During this process, the ejected electron known as photoelectron and characteristic x-ray emission are produced. The photoelectric absorption increases when interacts with higher atomic number of materials such as bone and metal objects.

Beam hardening effect occurs when the average beam energy increases, or the x-rays beam become harder as it passes through a high-density object. Polychromatic x-ray beam consists of individual photons with broad energy ranges. As the beam passes through a metal object, the lower energy photons will be absorbed more easily and rapidly compared to the higher energy photons. Therefore, most of the high energy photons will penetrate and the beam become harden at some point, resulting in the appearance of dark bands or streaks in between two dense objects, as shown in Figure 2.2 (Boas & Fleischmann, 2012).

Figure 2.2 Example of the appearance of dark bands of the metal artefact caused by beam hardening

Photons scatter is also one of the factors that caused metal-induced artefacts. Scatter is due to deflection of the photons from their original pathway after the interaction with the atom of the absorber. The deflected photons then hit the CT detector off the centreline (different from its original pathway), which is the area that the photons should not be (Gjesteby et al., 2016). These scattered photons are the low frequency signals and will generate the bright bands or streaks on the reconstructed CT image, as shown in Figure 2.3.

Figure 2.3 Metal artefact appearance with bright streaks or bands causes by photons scatter.

Photon starvation also causes the metal-induced artefacts. Photon starvation event usually occurs at areas with a high attenuation such as metal objects. It occurs when there are low or nearly zero counts of photons reach the CT detector (Barret & Keat, 2004). Due to this event, noisy projection will be produced, and it will also cause fine bright and dark streaks on the image, as shown in Figure 2.4.

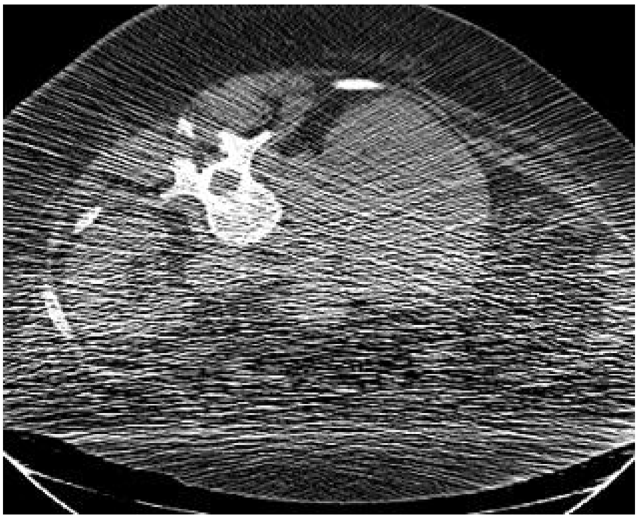

Figure 2.4 Metal artefact appearance in CT images caused by photon starvation

The NPLV effect (as shown in Figure 2.5) also contributes to the appearance of metal artefacts in CT images because the logarithm of the intensity detected by the CT detector is not equal to the integrated attenuation seen by the detector. Therefore, there is inconsistencies in the projection data, where the projection data is overlapping and inconsistent, which can cause streak in the image (Barret & Keat, 2004).

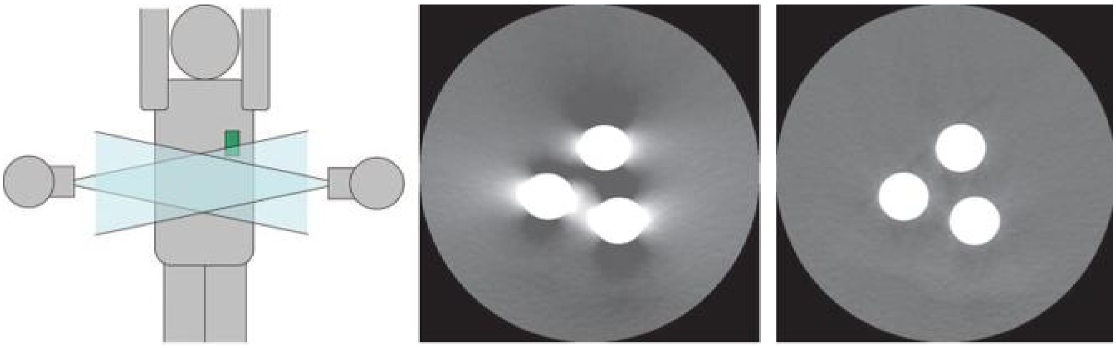

Figure 2.5 Appearance of metal artefacts due to NPLV effect (Barret & Keat, 2004)

The other factor that causes metal artefacts is undersampling. A large measurement interval between projection or undersampling is a result from misregistration by the computer during image reconstruction. The misregistration is related to information of sharp edges and small objects. This will produce aliasing which is the formation of fine lines or streaks on the CT images, as shown in Figure 2.6. Theoretically, the projection data should be sampled at half of the detector width or less to avoid aliasing (Gjesteby et al., 2016).

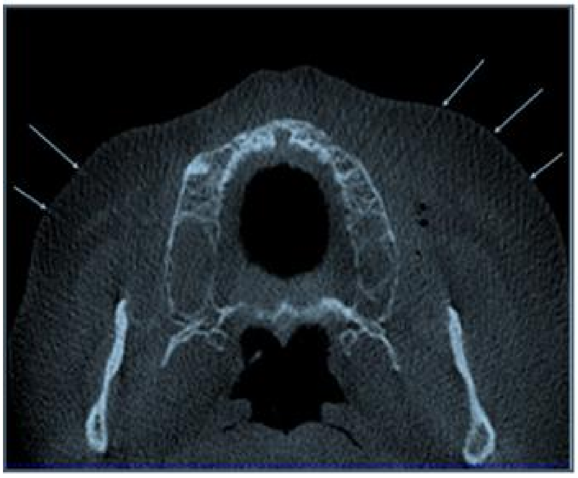

Figure 2.6 The appearance of artefacts on CT image due to aliasing.

The common source of metal artefacts is the existence of metal objects such as knee, hip and shoulder prostheses, spinal fusion implant, cardiac pacemaker implant and dental restoration such as dental fillings and tooth replacement. The size, shape and material that made up the metal objects determined the severity of the appearance of metal artefact on CT image. Metal objects with higher density such as stainless steel and gold will produce more severe metal artefacts while metal objects with lower density such as titanium and aluminum will produce less severe metal artefacts (Chen et al., 2012). The less severe metal artefact can be corrected by physics-based pre-processing. However, more severe metal artefact required modification of reconstruction algorithm such as sinogram interpolation or iterative reconstruction.

The major problems with the presence of metal artefacts in CT imaging are it may obscure the patient diagnosis and caused difficulties in distinguishing the important anatomical structures or pathologic conditions, inaccurate estimation of radioactivity in nuclear medicine and molecular imaging. Besides, it may also cause errors and uncertainties in treatment planning for radiotherapy such as anatomical target delineation and dose calculation (Lima et al., 2020; Rouselle et al., 2020).

2.2 Metal Artefacts Reduction (MAR) Algorithm

Several approaches have been proposed to reduce the metal artefacts in CT imaging in the past 40 years (Rouselle et al., 2020). Different methods were proposed based on the sources that induced the artefacts. The projection-based MAR algorithm mainly reduces artefacts that caused by photon starvation, whereas the dual-energy CT (DECT) technique (virtual monochromatic images obtained at low and high energy) mainly reduces the artefacts due to beam hardening effects (Katsura et al., 2018). One of the earliest methods proposed is to use higher tube current (mAs) and tube voltage (kVp) to increase the beam penetration and reduce the metal artefacts. However, this technique will increase the radiation dose to patient. Positioning the scan plane at the area without metal implant or least appearance of the implant can also reduce metal artefact but it might not be fully useful in every case (Saidun et al., 2019)

The most efficient approach is by using projection-based MAR algorithm to reduce metal artefacts in CT images. Most of the proposed approach mainly consists main steps such as metal segmentation or thresholding in the projection data, sinogram interpolation, and image reconstruction by back-projection (Katsura et al., 2018). There are several correction algorithms that have been proposed in reducing metal artefacts, mainly sinogram interpolation, iterative reconstruction, and hybrid MAR (Wang et al., 1996; Abdoli et al., 2010; Meyer et al., 2010; Boas & Fleischmmann., 2011).

2.2.1 Metal Thresholding

Thresholding is a technique used to differentiate different regions of the image. In this study, thresholding technique is the first part to identify and differentiate different regions within the sinogram. The metal part which contributes to the artefacts was detected and segmented using thresholding technique. There are few approaches that have been proposed. Manual thresholding by using light pen (Kalender et al.,1987) and simple thresholding (Duan et al., 2008; Abdoli et al., 2010; Faggiano et al., 2014) was used where the threshold values of metal part were identified manually. Other methods of thresholding were automatic thresholding (Yazdi et al., 2006; Zhang et al., 2007; Meyer et al., 2010; Meyer et al., 2012; Lell et al., 2012), Markov random field model (Veldkamp et al., 2010), mutual information maximized segmentation (Chen et al., 2012) and K-means clustering (Bal & Spies., 2006; Zhang & Wan., 2017). These approaches used approximation to detect and distribute the gray values to several classes automatically.

2.2.2 Projection-based Interpolation

Interpolation is a method of estimation of its surrounding values in constructing new data points. In MAR, interpolation is used to fill in and replace the missing data (thresholded region) of images. There are several interpolation methods that can be used in reducing metal artefacts. The most commonly projection-based interpolation methods used are sinogram interpolation, iterative reconstruction, and hybrid method.

2.2.2 (a) Sinogram interpolation

Sinogram is the 2D array of projections data of CT scan. Each row of the sinogram is the representation of image projection (measured intensity) for each rotation angle. The vertical axis (y-axis) of a sinogram is the distance from rotation centre in detector row while the horizontal axis (x-axis) is the angle of detector as shown in Figure 2.7 (Kalke & Siltanen., 2013).

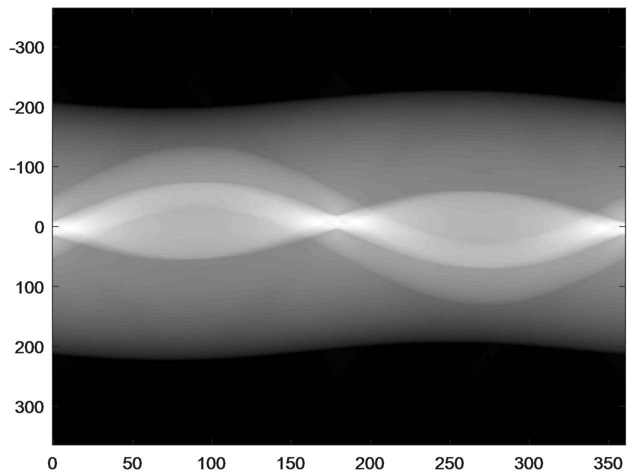

Figure 2.7 A sinogram of CT image shows the intensity plots at all the angles in one slice (viewed in MATLAB platform).

Sinogram interpolation (SI) is the most preferable method for metal artefacts correction because of its simplicity, time consumed and easier implementation. SI method is implemented by first, detecting and segmenting the corrupted data in the sinogram. Then, treating the projection data that corrupted by metal object as missing data (Meyer et al., 2010). Corrupted data due to the metal is segmented and detected by the method known as thresholding. The missing data is then replaced by in-painted data which generated by interpolation method. There are few methods for interpolation that has been proposed in previous studies such as polynomial interpolation, linear interpolation, wavelet interpolation, interpolation by contouring and cubic spline interpolation (Glover et al., 1981; Seitz & Rüegsegger., 1985; Kalender et al., 1987; Zhou et. al., 2000; Bruyant et. al., 2000; Meyer et al., 2010; Osman et.al., 2014).

From the previous work on interpolation technique in MAR, image with multiple metal implants and complex shape, or with complicated anatomical structures and structures with multiple densities will cause incomplete interpolation (Osman et al., 2014). It is because during the interpolation process, the missing data were not fully replaced. It will also cause loss of important anatomical information near the metal implant.

Kalender et al., (2006) proposed a simple MAR method using linear interpolation (LI). From this method, the corrupted data are identified and segmented manually. Then, LI method is performed to the nearest neighbouring data in order to replace the missing data. This method can generate new artefacts to the image because of the discontinuity in interpolation and it can be challenging for severe metal artefacts.

Then, in order to improve the discontinuity during interpolation, normalized metal artefact reduction (NMAR) method was developed by Meyer et al., (2010). In this study, 3D forward projections are used to detect the metal. The sinogram are normalized before interpolation is performed. The prior images are then segmented by using multi-threshold. LI is performed on the normalized sinogram and then denormalized again. From this study, it can be concluded that NMAR method produced a better result in reducing metal artefacts on the image compared to LI method (Abdoli et al., 2015). It also produced a nearly free artefacts image (Meyer., 2010).

Zhou et. al., (2000) introduced MAR method by using wavelet, where the sinogram is transformed to wavelet domain. The interpolation process is then performed in wavelet domain in between wavelet coefficients. The advantages of this method is it can suppress low frequency beam hardening artefacts and high frequency photon noise while keeping similar computational complexity as filtered back projection.

Bruyant et. al., (2000) developed a technique known as interpolation of projections by contouring (IPC). This method is implemented by using contour function in MATLAB to determine the set of contour lines in the sinogram. The points with equal intensity are connected and interpolation is used to fill in values at all pixels for each level line plot. Then, in order to reduce streak artefacts without increasing the scan acquisition time, the data were resampled to multiply the number of projections by two or three. From this study, the streak artefacts were reduced and no modification in acquisition is needed. This method is also not an operator dependent. However, the efficiency of this method reduces when the number of projections increases.

A sinogram total variation (TV) inpainting technique was employed by Zhang et.al., (2008). Thresholding is used to identify the region of metal object and the metal projection region (MPR) is attained from the reprojection of the metallic part. The MPR is determined and TV inpainting is used to fill the sinogram with MPR gaps. This method is better than linear interpolation method as it able to handle complicated cases such as image with multiple metal objects. It can also reconstruct image more accurately, in case of noisy projection data.

Chen et.al., (2012) employed an MAR method based on three major steps. The first step is prefiltering where the original CT image is enhanced using edge-preserving large scale non-local means (LS-NLM) filter. Then, by using mutual information maximized segmentation (MIMS) algorithm, the metal artefacts and metal objects are removed, and the image are separated into different regions. The third step is sinogram inpainting, where the segmented artefact image is forward projected to determine the affected projection data in the sinogram. The corrupted sinogram is subtracted from the original sinogram. Finally, the subtracted sinogram is restored and the image is reconstructed from in-painted sinogram using filtered backprojection. However, some improvement is needed for segmentation accuracy and inconsistency of intensity.

Osman et.al., (2014) introduced an MAR technique based on dual-step adaptive thresholding (DSAT). The DSAT technique is applied on the virtual sinogram, where the two high density regions in sinogram was segmented. This technique allowed a better and precise correction of the image. Then, the missing data were replaced by using cubic spline interpolation technique. From this study, the artefacts were suppressed, and the anatomical structures of the image was preserved. This technique also able to remove artefacts in image with single or simple shape of metal insert. However, further study is needed as this technique did not completely remove artefacts in image with multiple or complex shape of metal insert.

Zhang et al., (2007) used Laplacian diffusion method to replace the pixel inside the metal object with boundary pixels. This method was able to minimize the appearance of metal artefacts and improved the visibility of soft tissues near or away from metal objects. It also reduced the processing time.

Aderla et al., (2017) introduced a MAR method which incorporate magnetic resonance (MR) images. This method comprises of three main steps which are detection of metal, development of pseudo-CT and replacement of pixel in metal region. Firstly, a virtual sinogram is produced. Then, the metal region is detected and isolated to multiple classes using Otsu's thresholding. Three MR images based on different contrast settings are combined with the original CT image to produce pseudo-CT image, and then is forward projected to obtain the pseudo-CT sinogram. The purpose of pseudo-CT is to be used for replacing the corrupted values of the segmented sinogram. This method produced a better final image compared to LI method. It is also fast and fully automated. However, it needs a tri-modality set up which may not be available in all clinical centres.

2.2.2 (b) Iterative reconstruction

The iterative reconstruction (IR) method able to use prior knowledge of photon counting statistic and geometry of the scanner. This method has been successfully adapted to truncated and incomplete projection data situation. The main principle of the IR method is to do multiple repetitions of reconstruction until an ideal result is obtained. The IR method is made up of three major steps. Firstly, the forward projection of volumetric object is used to generate artificial raw data. Next, the artificial raw data is compared with the real measured raw data. This step is needed in order to compute the correction term. The last step is the backprojection of the correction data onto the volumetric object estimate. These three steps will be on the loop and it will finish when a particular specification has reached (Beister et.al., 2012).

Wang et. al., (1996) formulated two IR methods for MAR which are expectation maximization (EM) formulation and simultaneous algebraic reconstruction technique (ART). The EM-type IR method is based on two main processes, which are re-projection and backprojection. The initial estimation of the image to be reconstructed is made and it is re-projected along the x-ray paths in order to get the estimated projection terms. The measured projection data is divided by the estimated projection, backprojected from all orientations and then multiplied using pixel by pixel method to produce a better estimation. The steps are repeated until an acceptable result is obtained. It is shown that EM-type IR method converges faster than ART and has better image clarity. But it produced higher noise compared to ART.

Statistical method is another method used in IR, which include the statistics of detected photons in the process of image reconstruction. This method works in three different domains which are sinogram domain, image domain and the IR process. Kratz and Buzug (2009) developed a MAR method based on interpolation by using Non-equispaced Fast Fourier Transforms (NFFT). This method can be improved by the inclusion of prior data. The results are then reconstructed by using a weighted maximum likelihood expectation maximization algorithm (λ-MLEM). Finally, the results were evaluated and compared to one dimensional interpolation method. This method can reduce relative errors based on the ground truth in the image domain by more than 30% in comparison to linear and cubic interpolation.

The advantage of this method compared to filtered backprojection technique is it allows the integration of various physical model that helps in reducing noise and various artefacts in image. IR method can also contribute to reduction of radiation dose to the patient due to its precise modelling of the acquisition process. Moreover, the IR method used prior information, which can be an advantage in improving quality of the image, in combination with incomplete data and sparse.

However, IR method requires a high computational effort. Moreover, the computing power of the method is more complex, hence it requires longer computational time which is not efficient for clinical imaging process. This method also computationally intensive and expensive for clinical CT scanners (Wang et al.,1996).

2.2.2 (c) Hybrid method

Hybrid method is a combination of different categories of MAR method. Boas and Fleischmmann (2011) introduced metal deletion technique (MDT) method that uses the combination of LI and iterative method. The prior image is generated using LI. Then, the corrupted data are replaced using filtered back projection iteratively for four times. It can be concluded that this method reduces metal artefacts better than LI, however it is slower. This method also produced the lowest performance in reducing metal artefacts compared to 2D interpolation and NMAR (Abdoli et al., 2016).

Zhang and Wan (2017) proposed an MAR method by Euler's elastica inpainting. For segmentation, a *k*-means clustering is used to separate the metal and non-metal regions into several classes. A bigger *k* values or clusters is used for severe metal artefacts. In this study, Euler's elastica or 2D interpolation is used in order to better preserve the curvature and sharp edges of the sinogram. For a more severe metal artefact, iterative reconstruction will be applied to further reduce the metal artefacts. Euler's elastica inpainting method succeed in preserving the curvature and sharp edges of sinogram, therefore producing images with less artefacts. This method also outperforms LI and cubic interpolation.

2.2.3 Image Reconstruction

Image reconstruction is used to obtain the final image and is implemented after sinogram interpolation. Backprojection (BP) method has been used widely for its shorter computational time (Glover et al., 1981; Kalender et al., 1987; Duan et al., 2008; Abdoli et al., 2010; Meyer et al., 2010; Meyer et al., 2012; Lell et al., 2013). BP method involve mathematics term which is inverse Radon transform. Inverse Radon transform is where the sinogram of the CT image are backprojected and reconstructed into an image (Abdoli et al., 2010). This method is simple and efficient however, it may cause loss of projections and introduce additional artefacts.

2.3 Image Quality Evaluation

The effectiveness of the proposed method for metal artefact reduction is evaluated through image quality assessment or performance metric review. The image quality analysis was performed by comparing the original image that consist metal artefacts and the corrected image that consists mild or reduced artifacts using both quantitative and qualitative analysis.

2.3.1 Quantitative analysis

Quantitative evaluation also known as objective assessment on the image quality. Based on previous works, the quantitative evaluation was performed using the region of interest (ROI) analysis (Eslam and Abdelaziz, 2019; Yoo et al., 2018; Zhou et al., 2018). Few ROIs were drawn and placed near the metal implant regions where artifacts are present on the image slice (Zhou et al., 2018). The ROI was manually drawn as elliptical or circle using the image processing tool on the CT scanner workstation and the recommended ROI size was 40–60 mm^2 (Wei et al., 2020). Each ROI displays the attenuation (CT value or Hounsfield unit (HU)) and the noise or standard deviation (SD). These values were important to calculate and determine the image quality indices such as noise (N), signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR) and artefact index (AI).

Both the signal level and the noise level in given ROIs can be determine using SNR and CNR measures. The term SNR is defined as a measure of the mean value of image signal relative to its background noise in image, while CNR is defined as a measure of the contrast based upon attenuation difference between the subject contrast (tissue of interest) relative to the background noise (Seibert JA, 2004). CNR describes the contrast ratio or image signal difference from the background. Higher SNR and CNR values give better image quality as signal and contrast is higher than the image noise. As SNR and CNR reduced, the quantum noise is increased making it more difficult to visualise details of the image. Meanwhile, artefact index (AI) defines the differences between noise levels or standard deviation (SD) on the image with artefacts and reference image (without artefact) (Wei et al., 2020; Kawahara et al., 2019; Yoo et al., 2018; Dong et al., 2016). Higher AI value signifies higher degree of metal artefact on the CT image (Zhou et al., 2018).

2.3.2 Qualitative analysis

For qualitative evaluation or subjective assessment, the quality of CT images was assessed by experienced expert (observer) in diagnostic radiology. In most of previous work, the subjective assessment is performed by more than two radiologists with clinical experience more than 4-5 years in the related imaging procedure (Yoo et al., 2018;). The observers were blinded to any related image properties (blinded scoring) and they will independently analyse each image dataset for image quality assessment. The image quality was subjectively graded based on 5-point scales (Yoo et al., 2018; Hu et al., 2017) or 4-point scales (Wei et al., 2020; Zhou et al., 2018), but most of the recent study used 4-point scales for subjective assessment. The lowest score namely 0 represents the lowest image quality that describe image with severe artefacts, and the highest score namely 3 (for 4-points) and 4 (for 5-points) represents the optimum image quality that describe artefact-free image the clarity of the adjacent anatomical structures (Zhou et al., 2018).