Jurnal Sains Nuklear Malaysia, 2019, 31(1): 75 – 84
ISSN: 2232-0946

QUALITATIVE EVALUATION OF AN INDUSTRIAL X-RAY COMPUTED TOMOGRAPHY SYSTEM

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ABSTRACT

The invention of Computed Tomography (CT) has long been used for medical applications and material inspection. X-Ray Computed Tomography is a powerful imaging technique for viewing the interior of an object as if it had been sliced open along the image plane for viewing. The application of CT techniques has increasingly broadened in various industries i.e. aerospace, geoscience and archaeology. Malaysian Nuclear Agency has designed and developed an Industrial X-Ray CT system. The system consists of a 160 kV X-ray machine, a motorised linear rotary table, and X-scan linear array detector. 2-D CT image was acquired through the fan beam imaging modality. However, an X-ray CT does not provide information on the accuracy of the samples dimension and defects in terms of SI units. Another problems related to CT imaging is the alignment of X-ray fan beam with linear array detector (LAD) and formation of ring artifacts. In this work, methods for reducing ring artifacts are investigated like recalibrating the CT devices and ring filter application from CT reconstruction software. The alignment of X-ray fan beam with LAD by using dark films and VISI-X are described. Then, the dimension of CT sample can be estimated by calculating the geometrical magnification. The accuracy of geometrical magnification in estimating the size of CT sample is investigated by making a comparison with the measured magnification with varying position from X-ray source. Magnification is calculated by dividing the size of reconstructed CT sample with the measured size of actual CT sample.

Keywords: Alignment, dark films, linear array detector, magnification, ring artifacts, VISI-X, X-ray fan beam

INTRODUCTION

Computed Tomography (CT) is a non-invasive technique to produce images of "slices" through an object by utilising the principles of physics and mathematical concepts through the field of engineering and computer science. CT makes use of X-ray or gamma radiation to provide a 2-D or 3-D cross sectional view of the interior of an object as if it had been sliced open along the image plane for view. The cross-sectional image of the object's interior is reconstructed from X-ray transmission data collected by an array of detectors at many different angles. The invention of CT scanner revolutionized the field of medical diagnostic imaging because it provided detailed and vital information more than any previous non-invasive imaging techniques. The method is being used extensively for non-medical applications, particularly in industry, aerospace, geoscience, and archaeology. With the availability of advanced radiation detector systems and high speed computers, CT imaging of objects could be performed within seconds or minutes of its scan. By using X-ray, it is possible to study a broad range of samples, for example, metals, non-metals, objects with smooth and irregular surface and low to high-density materials. The choice of X-ray energy should suit the intended study to be carried out on such materials (Abdullah, 2008).

However, an X-ray CT system does not provide an information about the accurate dimension of a sample in terms of SI base units. It does not provide an information about the size, volume and density of a sample and any defects viewed in the cross-section image reconstructed from X-ray projection data. These data are crucial for the CT operator to make assessment on how large the holes and defects in an inspected sample as well as severity of damages. This complication can be solved by taking into account the image magnification. This could be accomplished by placing an object with known dimension at an optimal distance from the X ray source. The actual sample or defect size are estimated by incorporating the image magnification into the measurement of sample size taken from the CT image. Image magnification is heavily affected by the positioning of sample and center of rotation (COR).

Two different approaches have been used historically to cope with the problems connected with image magnification. The first was to develop mathematical theory on geometrical magnification on computed tomography dimensional measurements. Surprisingly, no ready answers exist in the literature as far as we are concerned. The second experimental approach was to use calibration objects with which to calculate magnification at some points on the image (Yuan, 2013). The second approach is described in this paper along with the basic optics equation for image magnification for comparison. The objective of this work is to investigate image magnification in vertical direction and how it was affected by the object's position. An alignment test for fan beam CT was also described in detail for the purpose of facilitating an accurate alignment of the central x-ray beam of the x-ray tube with a linear array detector. The X-ray fan beam formed by a collimator should be incident on all small detectors before scanning a CT sample.

In addition, poor pixel responses in linear array detector resulted in the appearance of ring artifacts in reconstructed CT image. X-ray CT machine is highly sensitive to small differences in the sensitivity of adjacent detector elements. This becomes important problem when highest contrast resolution is required. We suspect the hardware to be the main cause of these artifacts such as filter, detector or center of rotation (COR). A method of ring artifacts reduction is proposed here by utilizing ring artifact correction application in imaging software (Boas, 2012).

MATERIALS AND METHODS

Industrial X-Ray Computed Tomography System

The X-ray CT system consists of four major equipments: X-ray machine, linear array detector, PC controlled mechanical stage and a network of computers.

i. A 160 kV/10 mA industrial X-ray machine with 0.4 focal spot (IEC336) was used to provide X-ray beam penetrating through a CT sample in order to study its cross-sectional image. Tungten was used in the X-ray tube as the target material and beryllium window provided inherent filtration of the beam.
ii. The linear array detector (LAD) has gadolinium oxysulfide (GOS) as the scintillator material mounted on the surface of an array of photodiode. The LAD has a high dynamic range using a 12 bit ADC resolution and has a good spatial resolution from small pixel size of 0.4 mm (H) x 0.4 mm (W). The user performs calibration of the detector elements and turning on the LAD.

iii. The CT system utilised fan beam geometry with the fixed position of LAD, X-ray source, and the center of rotation (COR). The rotation table can be moved vertically and horizontally but not in z-direction. The source-to-detector distance (SD) were fixed at 1000 mm and source to object distance (SO) were changed in the experiment from 400 to 700 mm. Scanning of a CT sample took less than 20 seconds and image reconstruction is completed within less than 5 minutes.

Geometrical Magnification

One parameters related to operator is position of the measured part, and related to the parameter of geometrical magnification. Geometrical magnification is defined as the ratio between SD and SO distances (Equation 1).

$$Geometrical\ Magnification = \frac{SD}{SO} \tag{1}$$

5-Step aluminium calibration wedge with the length of 196 mm and custom square of thickness at 11.9 mm, 8.9 mm, 5.6 mm, 3.1 mm, and 1.9 mm was utilized as the CT sample to make a comparison between its dimension and the size of reconstructed image (Figure 1 and 2). Aluminium step wedge is commonly used in the calibration of X-Ray machines as well as analysis of X-ray beam quality (Margraf Dental Mfg. Inc., 2009). By positioning the step wedge closer to X-ray source, the larger resolution can be achieved but the reconstructed CT image results in less sharp edge projection. The SD is constant standard CT scan, so geometrical magnification depends only on SO distance (Novak, 2016). Observed were the actual length of aluminium step wedge, the length measured on X-ray beam projection image (obtained from sinogram image for the rotation of the CT sample by 360^o) and the length measured on reconstructed CT image. Then, the analytical comparison was made those three parameters. Note that this paper will only focus on vertical magnification with the assumption that the measured value of vertical magnification is approximately close with the overall value of geometrical magnification.

Figure 1: 5-step aluminum calibration wedge

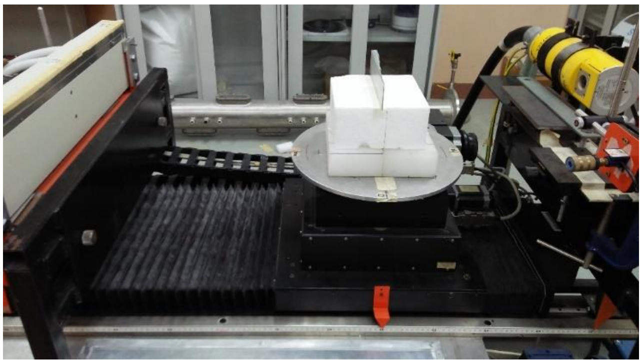

Figure 2: Industrial X-ray computed tomography imaging system using linear array detector with 5-step aluminium calibration wedge on the rotation table

The measurement of horizontal magnification will be passed over as the subject matter requires more thorough mathemathical theory and analysis. Table 1 presents scanning parameters set for all five cases, while in Table 2 are given SO distances and amounts of geometrical magnification as stated in Equation 1.

Table 1: Scanning parameters

Parameter	**Amount**
Voltage, kV	120
Current, mA	2.5
No. of Projection	1352
Detector Size, mm	0.4
Pixel Size	100x1450x10
FOC	1.0
Source-to-detector Distance (SD),	1000

Table 2: Source-to-object distance (SO)

Parameter	**Experiment No.**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
SO, mm	400	450	500	550	600	650	700
Geometrical Magnification	2.500	2.222	2.000	1.8181	1.667	1.538	1.428

X-Ray Fan Beam Alignment

The emergent X-ray cone-beam was collimated into a fan beam before penetrating a CT sample. Two alignment tools was employed to ensure the beam was focused on the linear array detector before the calibration of the detector elements and initiation of LAD:

i. Medical X-ray Green (MXG) Film is a high-speed, orthochromatic film for use with green light emitting intensifying screens such as LANEX Regular or LANEX Medium. It is coated on a blue, approximately 0.2 mm (7-mil) polyester support, with good static protection. It is designed for both standard high-throughput and rapid (RA) processing cycles (Carestream Health, Inc., 2014). Few MXG films are put in front of LAD facing the X-ray radiation field. Then, the films will be processed to obtain images (X-ray tube parameters: 110 kV, 0.5 mA) (Figure 3 and 4).

Figure 3: MXG films covered in X-ray film holders in front of LAD

Figure 4: MXG films on rotation table right at center of rotation (COR)

ii. Visi-X Field Position Analyzer is a cassette shaped instrument for checking the light and radiation field coincidence on X-ray equipment (Figure 5). The Visi-X is based on an after-glowing phosphorus screen. The X-ray room was darken before switch on the X-ray tube and Visi-X was put in front of LAD facing the X-ray beam. The light field was adjusted onto Visi-X. The radiation field will be immediately visualized by the glow of phosphor compound. This afterglow will last for several minutes (CSPMedical, n.d.).

Figure 5: Visi-X field position analyzer

Ring Artifacts Formation

Ring artifacts were first noticed in a reconstructed CT image of saturated water in 400 ml beaker. The set-up is a beaker filled with saturated water put on a rotational table right at the center of rotation (COR) (Figure 6). Then, ring artifacts in CT image was minimized to the smallest possible degree by utilizing ring filter application in Octopus Imaging Software (Figure 7). The cause of ring artifacts formation might be related to the failure of an individual detector element (or few) in LAD and the misalignment of CT sample with both X-ray source and COR. To overcome this defect, the experiment is repeated by aligning the COR of rotation table with the source with care, and the normalization procedure of LAD is repeated again to ensure each individual detector elements function properly.

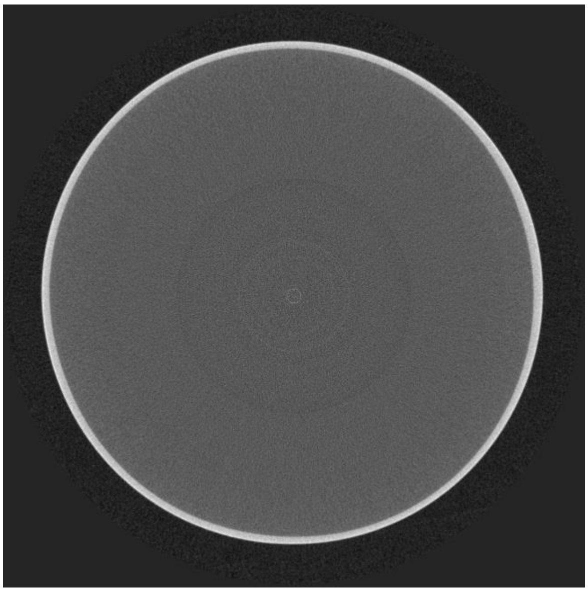

Figure 6: Ring artifacts surrounding the center of image

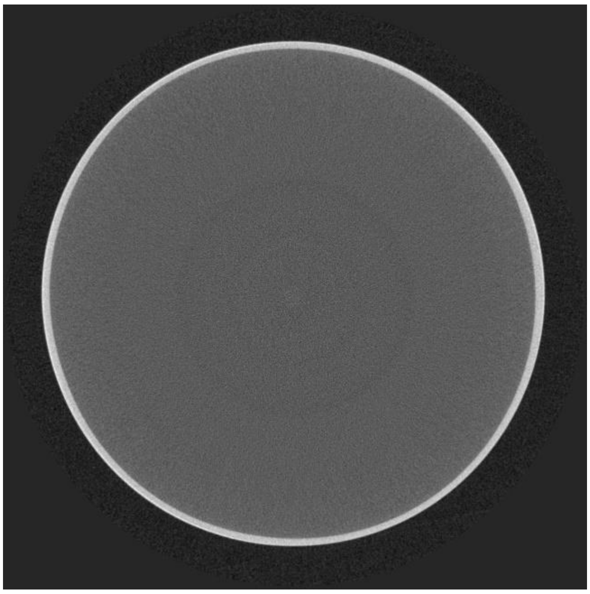

Figure 7: Ring artifacts were minimized by CT reconstruction software

RESULTS AND DISCUSSION

Geometrical and Image Magnification

The vertical length of aluminium step wedge is obtained from the projection data of sinogram and reconstructed image by using ImageJ software as dimension measurement tool. Magnification parameter in this experiment is defined as the ratio between the vertical size of sample captured in computed tomography system by linear array detector (LAD) over the actual size of the sample (Equation 2).

$$Geometrical\ Magnification = \frac{SD}{SO} = \frac{Vertical\ Image\ Size}{Vertical\ Sample\ Size} \qquad (2)$$

From the magnification formula (Equation 2), it is logical to assume that with the increase of (SO), the closer the distance between sample and LAD, and size of sample will decrease inversely approaching the actual size of sample. Results presented in Table 3 and Figure 8 show decline in amount of magnification almost reciprocally with the increase of source-to-object (SO) distance. Measured lengths decline with increase of source-to-object distance until the source-to-object distance reaches 196 mm which is the actual length of aluminium step wedge (magnification = 1). Deviations of magnification between sinogram, reconstructed image and geometrical magnification are caused by the measurement errors.

Table 3: Comparison between length measurement and magnification obtained from sinogram and reconstructed image

SO, mm		400	450	500	550	600	650	700
Geometrical Magnification (SD/SO)		2.500	2.222	2.000	1.818	1.667	1.538	1.428
Sinogram	**Length, mm**	472.4	423.6	383.6	350.4	322.8	298.8	278.0
	Magnification	2.410	2.161	1.957	1.788	1.647	1.524	1.418
Reconstructed Image	**Length, mm**	498.4	446.0	403.2	367.6	338.4	313.2	291.2
	Magnification	2.542	2.275	2.057	1.876	1.726	1.598	1.486

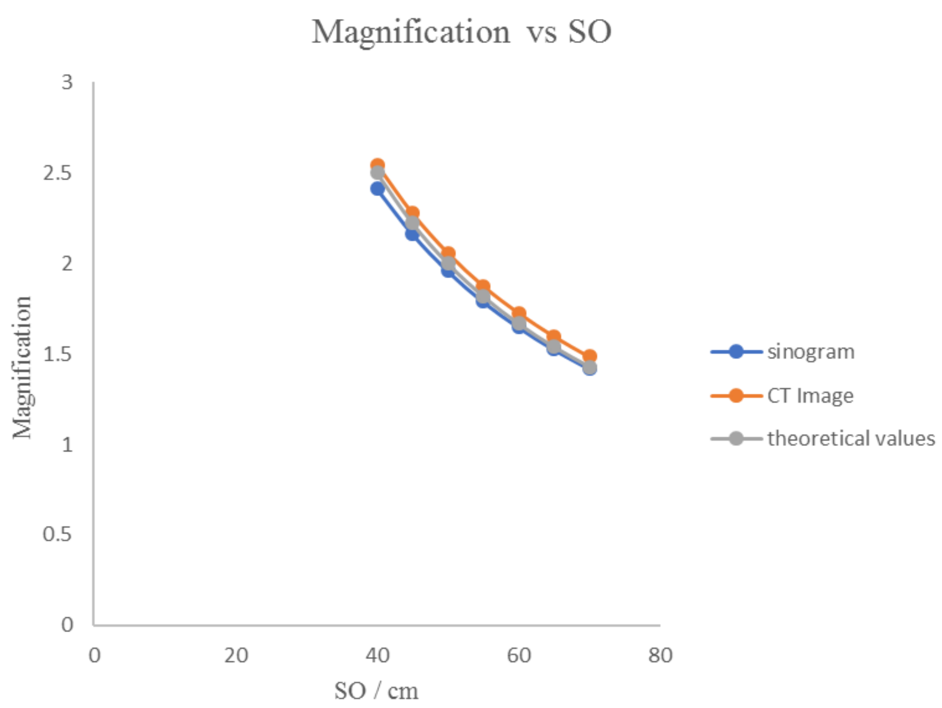

Figure 8: Image magnification measured from sinogram and reconstructed image with geometrical magnification forms almost inverse relationship with the increase of SO

Jurnal Sains Nuklear Malaysia, 2019, 31(1): 75 – 84
ISSN: 2232-0946

From the result, it can be concluded that the magnification values measured experimentally by scanning sample with varying horizontal position seems to be in good agreement with geometrical magnification calculated from theoretical calculation at SO distance of 400 mm to 700 mm from . The dimension of any computed tomography samples can be inferred directly by dividing image size with the geometrical magnification. For more precise measurement on certain position, the experiment can be conducted to obtain a magnification at that position, as the horizontal magnification may vary differently compared to vertical magnification.

Observation of X-ray Fan Beam Stripe on Photos

A line of black stripe will form over MXG films indicating the area penetrated by X-ray fan beam photons. Lead collimator with opening of 3 mm was utilized to narrow X-ray beam size into the direction of LAD pixels. In Figure 9 and 10, the films were overlapped together by using 7 needles as reference positions. Thickness of fan beam stripes in Figure 9 (at 400 mm from the source) and Figure 10 (at 1000 mm from the source) are 9 mm and 20 mm respectively. The reason for this is the increasing distance from the center (X-ray source) will cause the increase in X-ray scattering, and thus the thickness of X-ray fan beam increase as well. The light afterglow forming on Visi-X field position analyzer struck by X-ray fan beam form the same stripe shape as shown in Figure 10. The LAD pixels can be aligned together with the X-ray stripe image after the experiment with MXG films was done while the light afterglow on Visi-X vanished about 5 minutes after X-ray tube was switched off, so experiment is repeated with LAD pixels aligned precisely with the light stripe. From the figure, it is also observed that the intensity of X-ray beam decreases as the distance increases. It can be presumed that the X-ray beam emitted from the lead has uniform intensity throughout the whole stripe for efficient X-ray computed tomography scanning process.

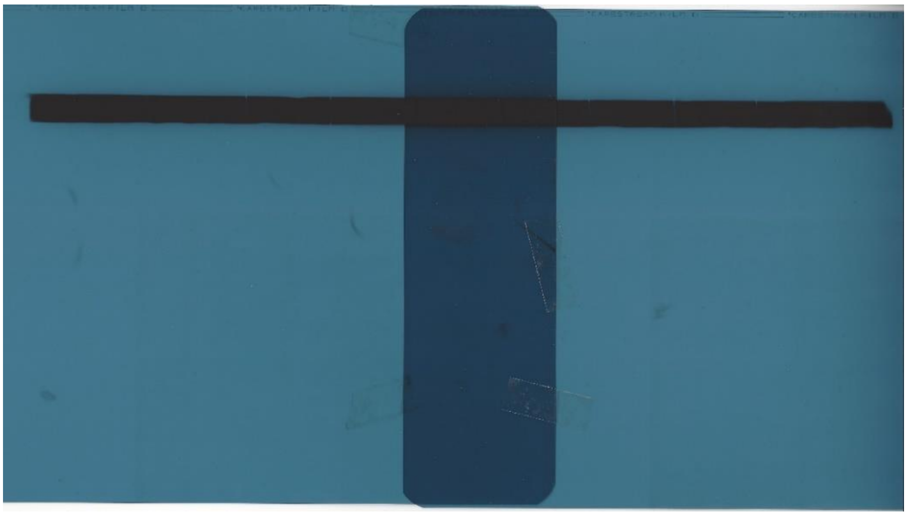

Figure 9: X-ray fan beam image on two MXG films put on rotation table right at center of rotation (COR). The images are overlapped together by using 7 needles as reference position for image alignment

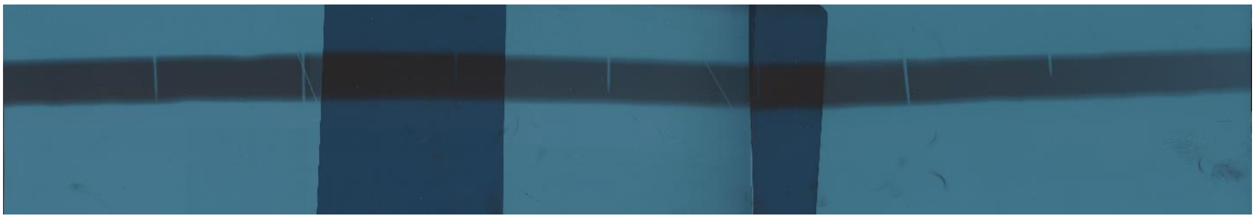

Figure 10: X-ray fan beam image on three MXG films put in front of LAD

Ring Artifact Reduction

Normalization procedure of LAD was repeated after realignment the center of rotation table with the point source was done to implement CT process on the sample. The small shift of rotation center from the center can cause inaccuracy in reconstruction algorithm process, and thus artifacts forming the closer it get toward image center. The reconstructed water image in Figure 11 shows a fair improvement compared with Figure 6 before the recalibration of X-ray device. Few ring artifacts are still there in the image which might be caused by small defects in LAD itself, the limits of calibration process, or motion artifact resulting from the stirring effect of water. In Figure 12, the image is improved using ring filter application from CT reconstruction software. Misstep in normalization procedure might also ruin the CT image and thus it needs to be handled with utmost care. Each individual LAD pixels detector needs to have a good response so any further ring artifacts do not occur or else the LAD should be replaced another with better individual detector responses.

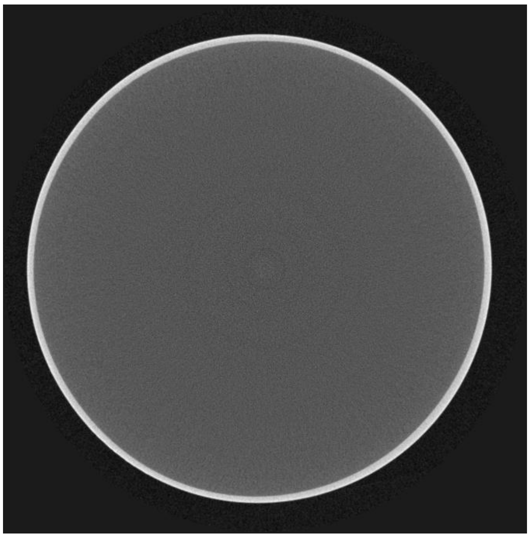

Figure 11: The ring artifacts reduced after recalibrating the center of rotation table and normalization of LAD

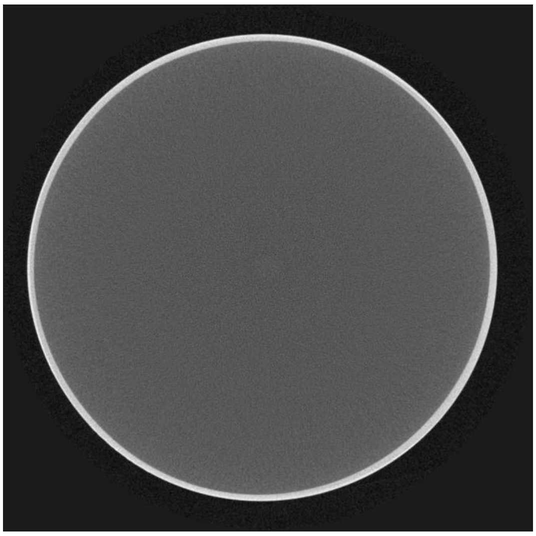

Figure 12: The ring artifacts minimized by CT reconstruction software.

CONCLUSIONS

In this paper, three evaluation methods on industrial X-ray computed tomography system was conducted for further calibration and development project on the system. It was shown that the geometrical magnification is in close agreement with the direct measurement of CT image from reconstruction software. Future works should include the evaluation of magnification for computed tomography sample at any given positions and the measurement uncertainty related with the parameters of X-ray CT system. The observation on the X-ray fan beam stripe on MXG films and Visi-X field position analyzer reveals a fine alignment of X-ray fan beam intensity over the LAD position. The ring artifact reduction technique utilized in this paper can minimize the ring artifact to a fine degree provided that the calibration of CT devices was implemented and LAD was in good condition. Another research can be done to eliminate another types of artifacts formed on reconstructed CT image.

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