Evaluation of image quality and radiation dose in kilovoltage cone beam computed tomography

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Abstract. This study was to evaluate the image quality and radiation dose of kV-CBCT when varying mAs and reconstruction filter. The radiation dosimetry (CBDIw) and quality control of kV-CBCT image were done. Routine protocols in head, thorax, and pelvis protocols were performed as a reference image. Then the images were acquired with varied mAs, the other parameters were fixed. Each technique was reconstructed with different filter. The image quality in terms of low contrast and high contrast resolution including CBDIw were compared. The result found that the variation of mAs with auto filter affected low contrast resolution, but slightly effect high contrast resolution. When mAs increased, low contrast detectability increased. Decreasing one step of mAs (16.67%) kept in acceptable image quality and reduced about 15% of CBDIw. The smooth filter improved the low contrast resolution, but it decreased the high contrast resolution. While the sharp or ultra-sharp filter improved the high contrast resolution. In conclusion, the changing of mAs affects the low contrast resolution and CBDIw. While the reconstruction filter changed the both of low and high contrast resolution, but no effect to CBDIw. To optimize the image quality and radiation dose of routine protocols, mAs can reduce one step-down.

1. Introduction
The image-guided radiation therapy (IGRT) used to verify the target localization before the treatment delivery and it can be improved the precision and accuracy. One type of IGRT is the kilovoltage cone beam computed tomography (kV-CBCT) which has a better image quality at a lower dose [1]. It applied in many clinical applications [2] such as prostate, lung, head and neck, breast, esophagus, liver, and bladder cancer. This work focused about the evaluation of image quality and radiation dose in the default kV-CBCT protocol in Varian Edge machine (Division of Stereotactic Radiosurgery at Ramathibodi hospital). Due to the long period treatment or daily IGRT in hypo-fractionated treatment, the additional dose of IGRT must be ignored. The cumulative dose should be concerned about secondary cancer in the future, especially in pediatric patients. The reviewed data of this system found that the common uses of kV-CBCT protocols are head, thorax, and pelvis protocols. Then, this study will evaluate in these three protocols by using the Catphan 504 phantom to test the image quality in terms of high and low contrast resolution to minimize radiation dose with the acceptable image quality for IGRT.
2. Materials and Methods

2.1 Displayed CBDI$_w$

The displayed CBDI$_w$ was verified before the dose difference of the default and optimized protocols was compared. The CTDI PMMA phantom and 100 mm cylindrical ionization chamber was used to quantify the radiation dose according to the studies of JG Buckley [3], HC Cheng et al [4], and A Amer et al [5]. The CBDI$_w$ value was calculated by the equation 1:

$$CBDI_w = \frac{1}{3} CBDI_{center} + \frac{2}{3} CBDI_{peripheral}$$ (1)

The percentage dose difference of measured and displayed CBDI$_w$ was calculated by the equation 2:

$$\%\text{Verification difference} = \frac{CBDI(\text{displayed}) - CBDI(\text{measured})}{CBDI(\text{measured})} \times 100$$ (2)

A criterion was passed in acceptable tolerance ± 20% according to the Radiation Protection No. 162 [6]. Then the percentage difference between the displayed CBDI$_w$ value of each optimized and default techniques in all protocols was calculated following the equation 3:

$$\%\text{Dose difference} = \frac{\text{displayed CBDI(optimized)} - \text{displayed CBDI(default)}}{\text{displayed CBDI(default)}} \times 100$$ (3)

2.2 Data acquisition of kV-CBCT

The kV-CBCT (PaxScan 4030 CB) integrated with linear accelerator machine manufactured by Varian Medical Systems was used. The quality control of kV-CBCT was performed by using Catphan 504 and all of procedures were in the acceptable tolerance following the Varian OBI manual. The reference images of Catphan 504 were performed by using the default parameters in head, thorax and pelvis protocols as shown in Table 1 to evaluate in terms of high and low contrast resolution. The variable mAs depended on the auto-adjustment of kV-CBCT system therefore the optimized image data were acquired with the two step-up and two step-down of the mAs values while the other parameters were fixed. The difference mAs in each step was 16.67%. In addition, each technique was reconstructed with the different filters composed of auto, smooth, standard, sharp, and ultra-sharp.

| Parameters                  | Head       | Thorax     | Pelvis     |
|-----------------------------|------------|------------|------------|
| Fan Type/Trajectory         | Full/Half  | Half/Full  | Half/Full  |
| kV                          | 100        | 125        | 125        |
| mAs                         | 150        | 270        | 1080       |
| Scan diameter (cm)          | 26.2       | 46.5       | 46.5       |
| Reconstruction filter       | Auto       | Auto       | Auto       |

2.3 Analysis and criteria of kV-CBCT Image

All of image data were assessed in terms of high contrast resolution and low contrast resolution which are the CTP 528 module and CTP 515 module of the Catphan 504 phantom, respectively. The high contrast resolution defined by the pattern of lines pair per centimetre (lp/cm). The detectability of low contrast resolution focused on supra-slice at 0.3%, 0.5%, and 1.0% contrast level (cl.). The zoom function can be applied as required. The criteria of the low contrast detectability was determined in terms of seen or unseen target. The visible seen more over 50% was categorized to the seen target. In the other hand, the lower than 50% seen was categorized to the unseen target.
3. Results

3.1 Displayed CBDI<sub>w</sub>
Table 2 shows the verification difference of displayed and measured CBDI<sub>w</sub>. In each protocol was in the acceptable tolerance (±20%). After verify the displayed dose, the percentage dose difference was performed and showed in Table 3.

| Protocol  | Displayed CBDI<sub>w</sub> (cGy) | Measured CBDI<sub>w</sub> (cGy) | %Verification difference |
|-----------|---------------------------------|---------------------------------|--------------------------|
| Head      | 0.32                            | 0.36                            | -11.11%                  |
| Thorax    | 0.40                            | 0.46                            | -13.04%                  |
| Pelvis    | 1.60                            | 1.88                            | -14.89%                  |

Table 3. The CBDI<sub>w</sub> and percentage dose difference in each protocol.

| Optimized mAs    | %Dose difference          |          |          |
|------------------|---------------------------|----------|----------|
|                  | Head                      | Thorax   | Pelvis   |
| Two step-down    | 0.21 cGy (-34.38%)        | 0.26 cGy (-35.00%) | 1.06 cGy (-33.75%) |
| One step-down    | 0.27 cGy (-15.63%)        | 0.34 cGy (-15.00%) | 1.34 cGy (-16.25%) |
| Default          | 0.32 cGy                  | 0.40 cGy | 1.60 cGy |
| One step-up      | 0.36 cGy (+12.50%)        | 0.46 cGy (+15.00%) | 1.86 cGy (+16.25%) |
| Two step-up      | 0.43 cGy (+34.38%)        | 0.54 cGy (+35.00%) | 2.14 cGy (+33.75%) |

3.2 Image Quality of kV-CBCT

3.2.1 High contrast resolution. The variable mAs slightly affected the high contrast resolution in head, thorax and pelvis protocols demonstrated in figure 1. The high contrast resolution of the default images in head, thorax and pelvis protocols were 6, 3, and 4 lines pair/cm, respectively. The results showed that step-down mAs only affected in pelvis protocol when using two step-down and two step-up mAs improved the observation of high contrast resolution in head and thorax protocols except pelvis protocol.

![Figure 1](image1.png)

**Figure 1.** The effect of varied mAs on high contrast resolution in each protocol.

![Figure 2](image2.png)

**Figure 2.** The effect of varied filter on high contrast resolution in each protocol.

The sharp and ultra-sharp filter affected the observation of high contrast resolution in head protocol but no effect in thorax and pelvis protocols (figure 2). It also found that the smooth filter decreased the high contrast resolution in pelvis protocol as shown in figure 3.
3.2.2 Low contrast resolution. As the result, the low contrast resolution in head protocol cannot detect due to the lower image quality. In default technique of thorax protocol, the number of low contrast targets at 1.0% cl. was 6 targets. The number of low contrast targets at 1.0%, 0.5% and 0.3% cl. improved when the mAs increased. While one step-down detected the number of low contrast target at 1.0% cl. same as the default technique but two step-down decreased the observation (figure 4). The smooth filter increased the detectability at 1.0% cl. whereas the sharp and ultra-sharp decreased the low contrast detectability as shown in figure 5.

![Figure 3](image)

**Figure 3.** The effect of varied filter on high contrast resolution in pelvis protocol.

![Figure 4](image)

**Figure 4.** The effect of varied mAs on low contrast resolution in thorax protocol.

Figure 6 shows the effect of variable mAs on the low contrast detectability in pelvis protocol. The default technique demonstrated that the number of low contrast targets seen at 1.0 % and 0.5% cl. were 7 and 5 targets, respectively. When the mAs was stepped down one and two steps, the number of low contrast targets seen at 1.0 % cl. was not changed from the default technique but at 0.5 % cl. decreased. On the other hand, the increasing of one and two step-up improves the more visible target seen at all of the contrast levels. However, it also increased the CBDIw value for 16.25 and 33.75%, respectively.

![Figure 5](image)

**Figure 5.** The effect of varied filter on low contrast resolution in thorax protocol.

![Figure 6](image)

**Figure 6.** The effect of varied mAs on low contrast resolution in pelvis protocol.

![Figure 7](image)

**Figure 7.** The effect of varied filter on low contrast resolution in pelvis protocol.
Figure 7 and 8 show the effect of reconstruction filter on low contrast targets and images of low contrast resolution in pelvis protocol, respectively. It demonstrated that the smooth filter can be improved the low contrast detectability at all cl. Especially at 0.3% cl. that cannot be detected with auto filter. The standard and sharp filter detected the targets equal to the auto filter. Notice that the ultra-sharp filter detected the lesser targets compared to the auto filter same as the thorax protocol.

![Figure 8. Low contrast resolution images in each filter of pelvis protocol.](image)

4. Discussion

In this study, the percentage difference of displayed CBDI \(_w\) between each step related to the different mAs step. The result showed that the CBDI \(_w\) is proportional to the mAs following the mention of Söderberg M. that the photon fluence is proportional to the mAs value \([7]\).

In general, the target localization of the head and pelvis protocols focus on bone structure represented to the high contrast resolution. While the thorax protocol focuses on soft tissue represented to the low contrast resolution. The one and two step-down of mAs did not affect high contrast resolution in head and thorax protocols but the two step-down slightly decreased the detectability in pelvic protocol. Whereas one step-down slightly increased the high contrast resolution in thorax protocol and two step-up slightly improved in head and thorax protocols but the one and two step-up of mAs increased the radiation dose 12.50% and 34.38% in head protocol and 15.00% and 35.00% in thorax protocol, respectively (which were unnecessary). The reason of the better high contrast resolution may come from the lower noise images when increasing mAs or radiation output. The variable mAs also affected the high contrast resolution and the CT resolution is limited by focal spot size, pixel size, sampling size, and reconstruction filter \([7]\). The high contrast resolution in the head protocol was higher than thorax and pelvis protocols due to the smaller pixel size. The matrix size was 512 \(\times\) 512, and the scan diameter in head protocol was 26.2 cm while in the thorax and pelvis was 46.5 cm. It is no reconstruction filter effect in thorax protocol but sharp and ultra-sharp filter can be improved the high contrast resolution in head protocol. It showed that smooth filter decreased the high contrast resolution in pelvic protocol but sharp or ultra-sharp filter affected the high contrast resolution follow as LW Goldman’s mention \([8]\).

In low contrast resolution, all of techniques in head protocol showed that it did not seen the low contrast target due to the lower mAs and the half trajectory of data acquisition. The half trajectory in head protocol using only 200 degree to acquire the data then then the image quality will be less than full trajectory with 360 degree. While the higher mAs and the full trajectory in the both of thorax and pelvis protocols made more low contrast targets seen. In the thorax protocol, at 1.0% cl. with the one step-down of mAs can be detected the low contrast equal to the default protocol. Moreover, the two step-down of mAs decreased the low contrast when compared to the default protocol due to the lower mAs value which affect the beam quantity and noise. The low contrast observation can improve by using the smooth filter. Besides, the one and two-step-up of mAs can improve to detect not only the number of targets seen at 1.0% cl. but also in the both of 0.5 % and 0.3% cl. In this condition, the CBDI \(_w\) increased 15% and 35% for one and two step-up of mAs, respectively. The smooth filter can increase the low contrast resolution, but the using of sharp and ultra-sharp filter more affected to decrease the low contrast detectability. In the pelvis protocols, the one and two-step-down of mAs gave the 1.0% cl. equal to the default protocol, but at 0.5% cl. was decreased. Moreover, the one and two step-up of mAs improved
the low contrast target seen in all of contrast levels. While the displayed CBDI increased 16.25% and 33.75% in one and two step-up of mAs, respectively. In addition, the smooth filter can improve the low contrast target seen due to the lower noise.

The mAs significantly affected the low contrast detectability. When the mAs was stepped down, the low contrast resolution decreased especially in two step-down. While the mAs was stepped up, the low contrast resolution increased due to the higher x-ray intensity and lower noise. Increasing of mAs is the increasing x-rays intensity and dose. In addition, the smooth filter affected the low contrast detectability.

5. Conclusions
The image quality of IGRT is required for the target localization in the patient setup verification of the advanced radiotherapy which must balance with the radiation dose. In practice, the settings of mAs value and reconstruction filter in each protocol depend on the desired target organ localization and patient size. In this study, the image quality related to the desired target organ localization was evaluated by using the Catphan 504 phantom. Therefore, the optimized parameters in each protocol are the guideline to apply in the routine before the usage in the patient. This study concludes that the one step-down of mAs can reduce the CBDI about 15% with acceptable image quality equal to the default protocol regarding the high contrast and low contrast resolution in all protocols. This finding also correlates to the study of N Teocharoen [9], and she mentioned that the reduction of mAs used in 25% in the thorax and pelvis protocol remains the image quality for target localization.

In case of a better low contrast detectability, the step-up of mAs used should be considered. Like the study of J wood [10] mentioned that soft tissue localization or large patient needs the more mAs used to achieve the acceptable image quality. Likewise, Kamath S [11] reported that the most image quality parameters improved with the increasing of mAs.

References
[1] Khan FM and Gibbons JP 2016 Khan's the physics of radiation therapy, Fourth edition (Philadelphia: Lippincott Williams and Wilkins)
[2] Bissonnette JP, Balter PA, Dong L, Langen KM, Lovelock DM, Miften M, et al. 2012 Quality assurance for image-guided radiation therapy utilizing CT-based technologies, A report of the AAPM TG-179 Med. Phys. 39 1946-63
[3] Buckley JG, Wilkinson D, Malaroda A and Metcalfe P 2017 Investigation of the radiation dose from cone-beam CT for image-guided radiotherapy: A comparison of methodologies J Appl Clin Med Phys. 176-80
[4] Cheng HC, Wu VW, Liu ES and Kwong DL 2011 Evaluation of radiation dose and image quality for the Varian cone beam computed tomography system Int J Radiat Oncol Biol Phys 80 291-300
[5] Amer A, Marchant T, Sykes J, Czajka J and Moore C 2007 Imaging doses from the Elekta Synergy X-ray cone beam CT system Br J Radiol. 80 476-82
[6] Radiation Protection No. 162 2012 Criteria for Acceptability of Medical Radiological Equipment used in Diagnostic Radiology, Nuclear Medicine and Radiotherapy 43
[7] Söderberg M 2008 Automatic exposure control in CT an investigation between different manufacturers considering radiation dose and image quality 9-10
[8] Goldman LW 2007 Principles of CT: Radiation Dose and Image Quality J Nucl Med Technol 35 213-25
[9] Teocharoen N 2012 A Dose Optimization Study in Kilovoltage Cone Beam Computed Tomography for Image Guided Radiation Therapy, Mahidol University 50
[10] Wood TJ, Moore CS, Horsfield CJ, Saunderson JR and Beavis AW 2015 Accounting for patient size in the optimization of dose and image quality of pelvic cone beam CT protocols on the Varian OBI system. Br J Radiol. 88 0364
[11] Kamath S, Song W, Chvetsov A, Ozawa S, Lu H, Samant S, et al. 2011 An image quality comparison study between XVI and OBI CBCT systems J Appl Clin Med Phys 12 376-90