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Evaluation of optimal kilovoltage-cone beam technique on image quality, registration accuracy, time of imaging and relative dose for head radiotherapy: A phantom study

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ABSTRACT

Background: Image-guided radiation therapy (IGRT) has improved geometry accuracy of patient positioning in radiotherapy. Nowadays, a kilo-voltage cone-beam computed tomography (kV-CBCT) is widely applied in IGRT to confirm daily patient positioning. However, one problem with IGRT is the increased dose to normal tissue outside the target area. Reduction in the dose of kV-CBCT verification imaging leads to deterioration in image quality and registration results.

Objectives: The objective of this study was to evaluate an optimal kV cone-beam technique on image quality, registration accuracy, relative dose, and imaging time using different combinations of angular range, angular separation, and mA (in total eight protocols) in the head phantom.

Materials and methods: Catphan® 503 phantom was used to evaluate image quality and a PIXY Anthropomorphic Training/Teaching Phantom was used to verify image registration accuracy. The kV-CBCT imaging was performed using an X-ray volumetric imaging (XVI) system mounted on an Elekta Versa HD linear accelerator. The absorbed dose of kV-CBCT imaging was determined using the head phantom with an ionization chamber. The eight protocols were analyzed for image quality, image registration, relative dose change, and imaging delivery time.

Results: Image quality parameter results showed that maximum contrast to noise ratio (CNR) increased by approximately 65% at 100 kV, 20 mA, θ=360°, and Δθ=0.54°, while uniformity compared with 100 kV, 10 mA, θ=200°, Δθ=0.54° (default protocol) varied within 7%. The spatial resolution showed no change (0.167 cm), with geometric distortions of less than 0.2 mm. Image registration errors were within 0.2 cm, with the highest magnitude of error seen in the vertical direction. Imaging dose can be reduced using 100 kV, 10 mA, θ=200°, Δθ=1.09° about 50% and 100 kV, 10 mA, θ=360°, Δθ=1.09° about 15% with similar CNR of default protocol. Imaging time decreased by approximately 2-folds, while Δθ increased by 2-folds.

Conclusion: The suggested protocols suitable for optimal kV-CBCT image quality, accuracy of image registration, decreased imaging time, and reduced image dose in the head region were 1) 10 mA, θ=200°, Δθ=1.09° 2) 10 mA, θ=360°, Δθ=1.09°, and 3) 20 mA, θ=360°, Δθ=1.09°. These protocols decreased imaging dose about 50%, 15%, and 2%, respectively. The developing kV-CBCT technique should be counterbalanced by careful consideration of imaging dose, image quality, imaging time, and accuracy of image registration.

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Introduction

The goal of radiotherapy is to deliver a high therapeutic prescribed dose to the tumor target while limiting treatment to the organ at risk (OAR). Radiotherapy techniques deliver doses to patients via a certain number of treatment fractions. This can cause deviations between planning dose distribution and delivered dose distribution, especially for high-precision techniques such as intensity-modulated radiation therapy (IMRT) and volumetric-modulated arc therapy (VMAT). Image-guided radiotherapy (IGRT) has recently been developed to detect target shifts relative to the target position in an approved radiotherapy treatment plan, such as kV-cone beam computed tomography (kV-CBCT). This generates 3D volumetric images of patient anatomy directly at the treatment site and uses the images to correct the set-up error during each treatment fraction.[1] Nowadays, kV-CBCT is used worldwide for patient positioning verification. However, the use of kV-CBCT imaging often results in additional patient radiation exposure to radiosensitive organs. Scandurra *et al*.[2] reported that an absolute dose of the head protocol was 0.9 cGy, while previous research indicated that image-guided kV-CBCT was effective for the evaluation of set-up accuracy.[3-6] Delishaj *et al*.[7] suggested that kV-CBCT should first be administered as three fractions and then followed by weekly doses to significantly reduce set-up errors in head and neck cancer treatment using the IMRT technique. Adequate management of the imaging dose is necessary for IGRT according to ICRP-60[8] although the dose delivered from kV-CBCT is small compared to the therapeutic dose. The AAPM task group 180[9] recommended that balancing the as low as reasonably achievable (ALARA) principle with the requirement for effective target localization required that imaging dose be managed by considering both the risks and benefits to the patient. Methods for reducing the kV-CBCT imaging dose include reduction of the tube current-exposure time (mAs), numbers of projections, and changing the imaging angle, filter, and scan length. However, reduction in the imaging dose leads to deterioration in image quality, and registration results may not be accurate.

The degrading effects on image quality and imaging dose of kV-CBCT have been studied by several investigators.[10-19] Image quality and imaging dose depend on the imaging system, while imaging dose depends on the frequency of the set-up related to the number of cancer patients at each treatment site. A continuous increase in patient numbers has impacted workloads at many treatment sites. Efforts have been made to decrease the time and frequency of kV-CBCT treatments. A 200 ° scan (180 ° plus the fan angle) has become the standard imaging configuration for head-and-neck cancers of all on broad imager (OBI) imaging. Short scan data contains high noise that impacts the registration matching process. The effect of reducing the image quality, while ensuring optimization of the imaging dose and registration accuracy, including time of imaging requires evaluation.

Purpose of this study was to evaluate an optimal kV-cone-beam technique on image quality, registration accuracy, relative dose, and imaging time using different combinations of angular range, angular separation, and mA in the head phantom

Materials and methods

CT simulation and planning

A CT simulator (Philips), Catphan® 503 phantom[20] was used to evaluate image quality, while a PIXY Anthropomorphic Training/Teaching Phantom (head phantom) was used to verify image registration accuracy. The scanning setting parameters were 100 kV and 350 mAs, with a slice thickness of 2 mm. The RayStation treatment planning system (RaySearch Laboratories, Stockholm, Sweden) was used for 3D-CRT planning of 6 MV photons in the brain and planning data was sent to the linac machine.

kV-CBCT imaging

kV-CBCT imaging was performed using an X-ray volumetric imaging (XVI) system mounted on an Elekta Versa HD linear accelerator (Elekta, Stockholm, Sweden). XVI software uses a cone-beam reconstruction process based on the Feldkamp-Davis-Kress algorithm.[21] The acquisition angle started from -90° in all protocols. The angular range (θ) used default settings for the head as 200° (half gantry rotation) and 360° (full rotation). The largest angular separation between views (Δθ) that can be used in XVI is 1.09°, while a default setting of 0.54° was used in this study. The θ and Δθ angles affect the number of projections about θ/Δθ. Therefore, the number of projections can be changed by modifying the gantry speed.

The default preset protocol of Lampang Cancer Hospital for head kV-CBCT is 100kV, 10 mA, θ=200°, and Δθ=0.54°. The absorbed doses were reduced by changing mA, θ, and Δθ. The current was tested at 10 and 20 mA, while angular ranges used in this study were θ=200° and 360° of gantry rotation. The angular separations of 0.54° and 1.09° were used in Δθ setting. Therefore, in total, eight protocols with different combinations were analyzed for image quality, image registration, relative dose change, and imaging delivery time.

Image quality analysis

The Catphan® 503 phantom is cylindrical with a diameter of 200 mm and length of 200 mm. It consists of three modules as CTP-404, CTP-486, and CTP-528 that were used to evaluate contrast-to-noise ratio (CNR), uniformity, and spatial resolution, respectively. The center of the Catphan® 503 phantom was positioned at the isocenter.

1. *CNR*. The CTP-404 module has sensitometry targets made from Teflon®, Delrin®, acrylic, polystyrene (PS), low-density polyethylene (LDPE), polymethylpentene (PMP), and air. The Hounsfield unit (HU) values in regions of interest (ROIs) of size 5×5 mm² within polystyrene and LDPE were calculated as follows:

$$\mathrm{CNR}=\frac{Mean_{PS} - Mean_{LDPE}}{SD_{PS} + SD_{LDPE}}\times 2$$

where $Mean_{PS}$ and $Mean_{LDPE}$ are the mean voxel values in PS and LDPE, respectively and SD_{PS} and SD_{LDPE} are the standard deviation in voxel values in PS and LDPE, respectively. CNR values of five slices were averaged and calculated for standard deviation.

2. *Uniformity*. The CTP-486 module as uniform water equivalent with a CT number of 20 HU was used to measure uniformity. Average values of 10 slices at the center of the phantom, with ROI sizes 10x10 cm^2 at the center and four peripheral positions were used to measure the HU values. Uniformity was calculated as follows:

$$\text{Uniformity}=1-\frac{Mean_{max} - Mean_{min}}{Mean_{max} + Mean_{min}}$$

A value close to 1 represents better image uniformity. The uniformity values of 10 slices were calculated for mean and standard deviation.

3. *Spatial resolution*. The CTP-528 module, composed of an epoxy background including a section of 21-line pair (LP) groups of 2 mm thick aluminum and two beads in the Z direction was used to measure spatial resolution. The 21 LP groups in the image were evaluated by the visual method.
4. *Geometric distortion*. This was evaluated as the maximum deviation from 50 mm of four spaced air holes drilled at 50 mm intervals in the CTP-404 module. The measurements were repeated 10 times to calculated the mean and standard deviation of geometric distortion.

For the statistical analysis, one-way ANOVA was used with SPSS version 17 (FB7E105EFD8A514130CC).

Image registration analysis

Image registration was analyzed using the head phantom. The planning CT images of the head were obtained by CT simulation (Philips) and transferred to the RayStation computer treatment planning system (RaySearch Laboratories, Stockholm, Sweden) to act as the reference image. The phantom was positioned correctly on the treatment couch of the Elekta Versa HD linear accelerator and then deliberately shifted 2.0 mm in the lateral, longitudinal, and vertical directions, respectively. The registration algorithm used an automatic registration based on bone matching in "Gray value mode", followed by a manual correction by the same technician. Deviation values of translation error from the table shifted 2.0 mm along the three axes were recorded.

Dose measurement

The absorbed dose in each protocol was determined using the head phantom (Fluke Biomedical, RMS) with an ionization chamber type IC RAD Model 6000-528 (Victoreen). The absorbed dose was measured three times for each protocol at the center of the phantom. The relative dose of each protocol was calculated and compared to protocol 100 kV, 10 mA, θ=200°, and Δθ=0.54° that was considered as the default protocol for the head in XVI.

Results

Image quality

Image quality parameters are listed in Table 1. At the fixed default protocol 10 mA, θ=200°, and Δθ=0.54°, the CNR decreased while Δθ increased. By contrast, CNR increased when θ and mA increased. Maximum CNR value increased by approximately 65% at 20 mA, θ=360°, and Δθ=0.54°. Uniformity compared with the default protocol varied within 7%, while CNR and uniformity of all protocols were not statistically different (p>0.05). All the protocols showed the same values of spatial resolution (0.167 cm), with geometric distortions of less than 0.2 mm.

Image registration

Translation vectors of image registration errors are shown in Table 2. The magnitude of error was within 0.2 cm for the vertical direction, with similar error was within 0.1 cm in both lateral and longitudinal directions. When parameters of θ and mA increased, the registration accuracy also increased.

Relative dose and imaging time

Relative dose variations of each protocol compared with the standard protocol and kV-CBCT imaging time are shown in Table 3. The protocol of 20 mA, θ=200°, and Δθ=1.09° gave a similar dose to the standard protocol. Maximum and minimum doses were 20 mA, θ=360°, Δθ=0.54°, and 10 mA, θ=360°, and Δθ=1.09°, respectively. With a fixed θ, imaging time decreased by approximately 2-folds while Δθ increased by 2-folds.

Table 1 Image quality parameters.

mA	θ	Δθ	CNR	Uniformity	Spatial resolution (cm)	Geometric distortion (mm)
10	200°	0.54°	3.97±0.66	0.86±0.01	0.167	0.17±0.32
		1.09°	3.19±0.54	0.87±0.03	0.167	0.15±0.17
	360°	0.54°	4.61±0.61	0.92±0.01	0.167	0.13±0.20
		1.09°	3.99±0.52	0.92±0.02	0.167	0.10±0.24
20	200°	0.54°	6.11±0.40	0.82±0.03	0.167	0.03±0.28
		1.09°	5.87±0.48	0.85±0.01	0.167	0.03±0.20
	360°	0.54°	6.54±0.54	0.89±0.02	0.167	0.03±0.30
		1.09°	5.95±0.42	0.90±0.02	0.167	0.03±0.26

Table 2 Image registration errors (cm) of the head phantom.

mA	θ	Δθ	Translation deviation (cm)		
			Lateral (x)	Longitudinal (y)	Vertical (z)
10	200°	0.54°	0.09±0.01	0.07±0.01	0.19±0.01
		1.09°	0.08±0.01	0.07±0.01	0.10±0.01
	360°	0.54°	0.03±0.00	0.08±0.01	0.10±0.01
		1.09°	0.03±0.00	0.08±0.01	0.08±0.01
20	200°	0.54°	0.08±0.01	0.07±0.01	0.10±0.01
		1.09°	0.08±0.00	0.07±0.00	0.10±0.01
	360°	0.54°	0.03±0.00	0.07±0.00	0.08±0.01
		1.09°	0.03±0.00	0.07±0.00	0.08±0.00

Table 3 Absorbed dose at the center of the head phantom and imaging time of kV-CBCT.

mA	θ	Δθ	Absorb dose (mGy)	Relative dose variation at isocenter (%)	Imaging time (sec)
10	200°	0.54°	12.87	default	72
		1.09°	6.47	-49.73	39
	360°	0.54°	21.70	68.61	121
		1.09°	10.90	-15.31	64
20	200°	0.54°	25.60	98.91	72
		1.09°	12.67	-1.55	39
	360°	0.54°	42.93	233.57	121
		1.09°	20.13	56.41	64

Discussion

This study evaluated the kV-cone beam technique. To achieve high image quality, high-level registration accuracy, optimized relative dose, and low imaging time were required using a combination of angular range and angular separation with decreased mA in the patient positioning set-up technique. Results will be useful to guide protocol selection in kV-CBCT for the head. kV-CBCT is an effective modern linear accelerator tool to ensure the accuracy and precision of patient set-up. However, how kV-CBCT imaging affects the dose in patients at about 2-3 cGy per fraction should not be ignored.[9] Parameters for increasing the angular separation and/or reducing the angular range, including the mAs reduction, can impact the result of image quality degradation and dose reduction. High CNR, high uniformity and small geometric distortions are useful indicators that generate high accuracy of image registration. This study showed high CNR at 20 mA, while using high mA increased the dose. CNR was increased using the protocol 20 mA, θ=200°, and Δθ=1.09° instead of using the default protocol with a similar absorbed dose. Changing from full scan (θ=360°) to half scan (θ=200°) altered CNR by about 7%, with the same angular separation in 20 mA, Δθ=0.54° and by about 25% in 10 mA, Δθ=1.09° protocol. For the same angular range, CNR was high when using angular separation at Δθ=0.54°. Maximum percentage change between using Δθ=0.54° and 1.09° was 10 mA, θ=200° at about 20%. Results showed that angular range impacted CNR more than the angular separation in protocol of 10 mA, concurring with Men and Dai[10] who found that CNR increased by about 2 times from θ=260° to θ=360°, while Δθ was little change. For protocol of 20 mA, the high change was recorded in angular separation of θ=360° about 9%, while angular separation had slightly more impact than angular range. The angular range, angular separation, and mA affected CNR and uniformity but changes in values were not significant, while spatial resolution showed no change. Geometric distortion changed in protocol of 10 mA (within 0.2 mm) but with no significant change in different mA values. However, Takei *et al.*[17] reported that a geometric distortion was within 0.1 mm of low dose head protocol. The kV-CBCT image quality is sensitive to many factors[22] including scattering and beam hardening effects.

Registration results using automatic and manual gray value mode matching methods compared between CT simulation images and kV-CBCT images showed deviations within 0.2 cm of all protocols, although the CNR value of image quality decreased by 19% in 10 mA, θ=200°, Δθ=1.09° from default protocol. The kV-CBCT image of the head phantom had high contrast details in the cranial bone and brain tissue, including spatial resolution of kV-CBCT did not change. Therefore, automatic image registration software can be used to accurately determine the anatomical structure. Hardware and software related to OBI imaging have recently been improved by manufacturers. Changes in the kV-CBCT scan settings have increased image quality and can be used to reduce doses. One limitation of this study was the use of a solid phantom to perform accurate image registration more than in patients because of varied patient contour and anatomy structure. The imaging dose measurement was also influenced by the position of the isocenter and the dimensions of the patient. Different physiques of patients cause variation of both image quality and imaging dose. The evaluation of accurate registration and image dose of actual patients is very difficult. Therefore, phantom should first be studied before application in patients. Nowadays, image guidance has become an integral part of the radiotherapy treatment process. The undoubted advantages should be counterbalanced by careful consideration of imaging dose, image quality, accuracy of image registration, and time of imaging. The relative dose compared with the default technique can be reduced by increasing the angular separation. The suggested protocols suitable for optimal kV-CBCT image quality with accurate image registration in the head region were 10 mA, θ=200°, and Δθ=1.09° or 10 mA, θ=360°, and Δθ=1.09°. These protocols also reduced dose and imaging time. The 20 mA, θ=200°, and Δθ=1.09° protocol is recommended for increasing image quality and reducing imaging time, while maintaining the imaging dose of the default protocol.

Several studies have evaluated reductions to the imaging dose of kV-CBCT.[23-28] Daily doses to the soft tissue resulting from current kV-CBCT imaging were less than results from using an electronic portal imaging device (EPID). However, a few reports have reported on kV-CBCT imaging protocol as suitable for reducing imaging dose using optimal image quality, image registration accuracy, and imaging time. This study assessed radiation exposure to imaging quality and image registration from kV-CBCT and also offered the technician alternative suitable techniques. Lu *et al*.[23] revealed that using CBCT decreased the imaging dose by reducing the number of projections, while Men and Dai[10] evaluated angular range and separation on image quality, image registration, and imaging dose. Takei *et al*.[17] reported registration accuracy at low dose kV-CBCT. However, an evaluation of the correlation with imaging time was not performed. The time required for image verification is important in institutes that have large patient workloads and limited numbers of linac machines. Small numbers of projections by reducing the angular range and increasing angular separation can decrease imaging time. A half scan can reduce imaging time by 2-folds using half angular separation. High efficiency of position set-up to verify imaging can be achieved by choosing a suitable procedure to balance image quality and patient dose. The development of protocols using image-guidance procedures is urgently required.

Conclusion

The kV-CBCT imaging protocol can be used different combinations of angular range and angular separation with decreased mA to setting suitable protocol for patient verification. Results suggested protocols suitable for optimal kV-CBCT image quality similar to the default protocol at 10 mA, θ=200°, and Δθ=0.54°, and accuracy of image registration within 0.2 cm in the head region as 10 mA, θ=200°, and Δθ=1.09° to reduce imaging dose and imaging time by about 50% or using protocol of 10 mA, θ=360°, and Δθ=1.09° to decrease imaging dose and imaging time by about 15%. To increase the CNR value with slight change of imaging dose, protocol of 20 mA, θ=200°, and Δθ=1.09° is recommended. The developing optimize kV-CBCT imaging protocol should be optimize imaging dose, image quality, accuracy of image registration, and imaging time.

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