Received:
26 May 2015

Revised:
24 July 2015

Accepted:
29 July 2015

doi: 10.1259/bjr.20150425

Cite this article as:

Yoganathan SA, Maria Das KJ, Maria Midunvaleja K, Gowtham Raj D, Agarwal A, Velmurugan J, et al. Evaluating the image quality of cone beam CT acquired during rotational delivery. *Br J Radiol* 2015; **88**: 20150425.

FULL PAPER

Evaluating the image quality of cone beam CT acquired during rotational delivery

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Objective: The aim of this work was to evaluate the quality of kilovoltage (kV) cone beam CT (CBCT) images acquired during arc delivery.

Methods: Arc plans were delivered on a Catphan® 600 phantom (The Phantom Laboratory Inc., Salem, NY), and kV CBCT images were acquired during the treatment. The megavoltage (MV) scatter effect on kV CBCT image quality was evaluated using parameters such as Hounsfield unit (HU) accuracy, spatial resolution, contrast-to-noise ratio (CNR) and spatial non-uniformity (SNU). These CBCT images were compared with reference scans acquired with the same acquisition parameters without MV “beam on”. This evaluation was carried out for different photon beams (6 and 15 MV), arc types (half vs full arc), static field sizes (10 × 10 and 25 × 25 cm²) and source-to-imager distances (SID) (150 and 170 cm).

Results and Conclusion: HU accuracy, CNR and SNU were considerably affected by MV scatter, and this effect was increased with increasing field size and decreasing photon energy, whereas the spatial resolution was almost unchanged. The MV scatter effect was observed to be more for full-rotation arc delivery than for half-arc delivery. In addition, increasing the SID resulted in decreased MV scatter effect and improved the image quality.

Advances in knowledge: Nowadays, volumetric modulated arc therapy (VMAT) is increasingly used in clinics, and this arc therapy enables us to acquire CBCT imaging simultaneously. But, the main issue of concurrent imaging is the “MV scatter” effect on CBCT imaging. This study aims to experimentally quantify the effect of MV scatter on CBCT image quality.

INTRODUCTION

In the era of conformal radiotherapy, dose distributions can be planned tightly around the target with minimal dose to critical organs. But, the actual dose delivered to the patient may not be as conformal as the plan owing to changes in tumour position with respect to treatment isocentre.^{1–4} The tumour motion in radiotherapy is classified into intra- and interfractional motions. Advancements in radiotherapy resulted in image-guided radiotherapy (IGRT) techniques to handle the intra- and interfractional target motions.^{5–7} Nowadays, gantry-mounted IGRT systems are commonly available in clinics to acquire both two-dimensional (2D) and three-dimensional (3D) verification images.

Generally, these verification images are acquired prior or after treatment, and the target position or shape determined by these images may not be constant during treatment.^{8,9} Hence, we need to continuously image the dynamic targets during treatment either for adapting the treatment beam aperture (*i.e.* tracking) or for knowing

the actual tumour position/shape, and this requires simultaneous megavoltage (MV)-kilovoltage (kV) “beam on”.^{10–12} The simultaneous imaging provides self-assurance that the actual treatment is delivered to the right area. In addition, it also reduces the total treatment time by acquiring verification imaging simultaneously with treatment delivery. At present, there are two clinical situations where we need to use simultaneous MV-kV beam on. Firstly, in real-time tracking delivery, simultaneous MV-kV beam on is used. Wiersma et al¹⁰ demonstrated a near real-time 3D internal fiducial tracking system based on the combined use of kV and MV imaging (2D) in a Varian Trilogy™ (Varian Medical Systems, Palo Alto, CA) system equipped with on-board imaging (OBI) to know the 3D position of moving targets. Secondly, techniques have been proposed to acquire volumetric imaging during arc treatment delivery, which also requires simultaneous MV-kV beam on. Nakagawa et al¹² demonstrated the first clinical cone beam CT (CBCT) imaging during volumetric modulated arc therapy for understanding the change in prostate position

Table 1. Quality of cone beam CT images acquired at 150-cm source-to-imager distance

Parameters	Half arc					Full arc				
	Ref. ^a	6 MV		15 MV		Ref.	6 MV		15 MV	
		10 × 10 cm ²	25 × 25 cm ²	10 × 10 cm ²	25 × 25 cm ²		10 × 10 cm ²	25 × 25 cm ²	10 × 10 cm ²	25 × 25 cm ²
Air	−998.0	−931.3	−780.2	−957.6	−835.4	−987.6	−864.0	−733.2	−948.6	−856.5
PMP	−196.1	−208.1	−254.3	−201.4	−229.3	−192.2	−224.6	−320.7	−203.7	−240.8
LDPE	−99.1	−126.4	−191.0	−113.7	−154.8	−96.0	−149.1	−276.1	−116.3	−165.2
Polystyrene	−47.4	−113.5	−242.9	−66.4	−124.9	−47.4	−113.5	−242.9	−70.2	−127.3
Acrylic	122.0	60.2	−67.7	80.3	−14.7	109.7	7.3	−185.7	69.1	−17.5
Delrin	342.1	240.2	51.8	208.6	−12.0	326.5	184.1	−87.8	274.1	142.8
Teflon	999.0	795.0	415.9	861.7	572.0	959.7	669.8	184.6	855.8	597.3
Contrast-to-noise ratio	18.8	13.3	10.3	15.0	10.9	22.7	20.4	10.4	28.8	22.0
Spatial non-uniformity	1.3	0.5	1.2	1.3	1.6	1.2	3.1	8.3	1.9	5.8
Spatial resolution (lp cm ^{−1})	9.0	8.0	8.0	9.0	8.0	5.0	5.0	5.0	5.0	5.0

LDPE, low-density polyethylene; PMP, polymethylpentene.

^aReference scan values (without megavoltage beam on).

and shape during treatment delivery. In these circumstances, excellent visibility of the target and critical organs in verification imaging is important. But, the real problem in acquiring kV images during treatment is the MV-scattered photons reaching the kV detector. This MV scatter would add noise to kV imaging and degrade image quality.^{13–17} Similarly, Ng *et al*¹⁸ also developed an X-ray system called kilovoltage intrafraction monitoring (KIM), which can be used to determine 3D tumour positions during arc treatment delivery. They successfully implemented this simultaneous kV on ten patients with clinical prostate cancer.

Luo *et al*¹³ analysed the 2D image quality of a real-time target-tracking system using simultaneous kV-MV imaging. The contrast-to-noise ratio (CNR) was used to describe the visibility of gold markers placed in a thorax phantom, a dynamic phantom and a pelvis phantom. It was concluded that the MV beam scatter effect on kV imaging during simultaneous MV-kV imaging was significant, and the kV beam scatter effect on MV imaging was minor. Their study investigated the MV scatter effect only on 2D kV images; however, a comprehensive evaluation of MV scatter effect on 3D imaging (kV CBCT) has not been carried out.

Therefore, we intend to investigate the image quality of kV CBCT acquired during arc delivery. The MV scatter effect was studied as a function of MV beam energy, arc type, kV imager distance and field size.

METHODS AND MATERIALS

Image acquisition

Half-rotation and full-rotation arc plans were generated for 6-MV photon beams with a dose rate of 400 MU min⁻¹ for two static field sizes of 10 × 10 and 25 × 25 cm² using Varian Eclipse™ treatment planning system v. 8.6 (Varian Medical Systems). The gantry start-stop angle for the half-rotation arc was 178°–22° (clockwise), and the total monitor unit (MU) for the delivery was 272 MU, whereas the gantry start-stop angle for full-rotation arc was 184.1E°–180.1° (counter clockwise), and the total MU for the delivery was 406 MU. The total MU of half and full arc was selected in such a way so as to restrict the gantry to move at maximum speed, approximately 6° s⁻¹.

These plans were delivered on a Catphan® 600 phantom (The Phantom Laboratory Inc., Salem, NY), which was aligned to the isocentre of a medical linear accelerator (linac) (CL 2100 CD; Varian Medical Systems). The linac has dual photon beams (6 and 15 MV) with a maximum deliverable dose rate of 600 MU min⁻¹, and it is equipped with the OBI system v. 1.5 (Varian Medical Systems) attached orthogonally to the MV beam. The OBI system contains a kV source and a flat-panel detector (aSi 1000) which are attached to the robotic control arms for accurate positioning. The maximum field size at the isocentre that can be covered by the kV detectors is 40 × 30 cm². The pixel size and resolution of the kV detectors were 1024 × 768 and 0.0391 cm, respectively. During treatment delivery, kV CBCT images were simultaneously acquired by positioning the detector at 50 cm from the isocentre [source-to-imager distance (SID) 150 cm]. During half-arc treatment delivery, the full-fan mode was used for CBCT imaging, with the kV imaging panel

Figure 1. Reconstructed slices of Catphan® 600 (The Phantom Laboratory Inc., Salem, NY) acquired during full-arc [half-fan cone beam CT (CBCT) mode] treatment delivery at a 150-cm source-to-imager distance. (a) Reference scan (without MV scatter); (b) scatter effect of 6-MV arc delivery with a field size of $10 \times 10 \text{ cm}^2$; (c) scatter effect of 6-MV arc delivery with a field size of $25 \times 25 \text{ cm}^2$; (d) scatter effect of 15-MV arc delivery with a field size of $10 \times 10 \text{ cm}^2$; (e) scatter effect of 15-MV arc delivery with a field size of $25 \times 25 \text{ cm}^2$. All images are shown with the same window width and level. MV scatter produces a cupping effect, and it is higher for the 6-MV beam and a field size of $25 \times 25 \text{ cm}^2$.

symmetric (field of view 25 cm) about the isocentre and a full-fan bow-tie filter (symmetric). Similarly, during full-arc treatment delivery, the half-fan mode was used for CBCT imaging, with the lateral kV imaging panel offset (field of view 45 cm) and a half-fan bow-tie filter (asymmetric).

The typical setting of 125 kV, 80 mA and 20 ms was used for CBCT acquisition. The images were reconstructed for 2-mm slice thickness with 512×512 pixel size. Since, simultaneous MV and kV beam on was not possible in the clinical mode of the linac, it was carried out in the service mode. It was

observed that increasing the SID decreased the scatter in digital radiography,¹⁹ and the same approach was used for reducing MV scatter. In order to investigate the influence of the SID on MV scatter, additional kV CBCT images were acquired at a SID of 170 cm for the above arc treatments. The 170-cm SID is not common in routine clinics; hence, additional CBCT modes were created in OBI. Calibration tests were performed for these new modes as per the OBI maintenance manual.²⁰ Similarly, the same experiments were repeated for 15 MV to quantify the effect of higher energy.

Evaluation of image quality

The Catphan 600 phantom contains various modules for evaluating the image quality of 3D images. The CBCT images acquired during arc treatment delivery were compared with “reference scans” acquired with the same acquisition parameters without MV beam on. The MV scatter effect on kV CBCT image quality was quantified using parameters such as HU accuracy, CNR, spatial non-uniformity (SNU) and spatial resolution.

Figure 2. Reconstructed slices of Catphan® 600 (The Phantom Laboratory Inc., Salem, NY) acquired at 150 cm. These images were acquired during 6-MV arc treatments with a field size of $25 \times 25 \text{ cm}^2$. (a) Images of half-arc [full-fan cone beam CT (CBCT) mode] delivery; (b) images of full arc (half-fan CBCT mode) delivery. All images are shown with the same window width and level. The cupping effect was considerably higher for full-arc delivery.

HU number accuracy was evaluated using the CTP404 module of the phantom which has seven sensitometry targets. Average CT numbers were measured within a square region of interest (ROI) placed at the centre of each target; the ROI size of 9×9 and 15×15 pixels was used for full-arc and half-arc CBCT images, respectively. The same module was also used to measure the CNR. For CNR measurement, mean HU value of delrin $[(\text{MeanHU})_{\text{Del}}]$ the target was recorded by placing a ROI at the centre of the target. Subsequently, a second ROI of the same area was placed adjacent to the delrin target, and the mean HU value $[(\text{MeanHU})_{\text{BKG}}]$ and standard deviation

Table 2. Quality of cone beam CT images acquired at 170 cm source-to-imager distance

Parameters	Half arc					Full arc				
	Ref. ^a	6 MV		15 MV		Ref.	6 MV		15 MV	
		10 × 10 cm ²	25 × 25 cm ²	10 × 10 cm ²	25 × 25 cm ²		10 × 10 cm ²	25 × 25 cm ²	10 × 10 cm ²	25 × 25 cm ²
Air	-998.5	-922.8	-752.7	-955.8	-819.4	-995.9	-996.9	-851.2	-984.4	-903.3
PMP	-192.2	-196.6	-216.5	-195.7	-199.7	-192.0	-201.9	-244.7	-199.2	-223.0
LDPE	-98.1	-113.7	-154.0	-106.5	-128.6	-95.5	-117.3	-174.1	-110.5	-148.0
Polystyrene	-31.5	-59.2	-116.7	-46.9	-87.2	-39.3	-67.9	-129.2	-56.8	-96.7
Acrylic	141.8	93.0	-4.7	109.2	39.0	125.3	80.4	-17.7	95.9	31.9
Delrin	348.5	278.0	117.1	301.4	186.4	338.5	290.4	137.6	315.9	210.7
Teflon	1028.1	828.8	476.0	894.2	627.9	1003.9	863.4	553.1	911.8	693.2
Contrast-to-noise ratio	18.2	16.5	11.2	18.0	13.8	28.3	27.4	20.6	31.2	20.8
Spatial non-uniformity	2.0	2.9	4.2	2.4	3.4	1.5	1.4	6.7	1.2	4.6
Spatial resolution (lp cm ⁻¹)	8.0	8.0	8.0	8.0	8.0	5.0	5.0	5.0	5.0	5.0

LDPE, low-density polyethylene; PMP, polymethylpentene.

^aReference scan values (without megavoltage beam on).

$[(STD)_{BKG}]$ of the background were recorded. The CNR was calculated as follows:

$$CNR = \frac{(\text{MeanHU})_{\text{Del}} - (\text{MeanHU})_{\text{BKG}}}{(STD)_{\text{BKG}}}$$

SNU was measured using the CTP486 module, which consists of uniform water-equivalent material. Average CT numbers were measured within square ROIs as above, which were placed at five different positions (at the centre and the peripheries at the top, bottom, left and right) as recommended in the Catphan user manual.²¹ From these five values, the SNU was calculated using maximum (HU_{Max}) and minimum HU (HU_{Min}) values as shown in following formula:

$$SNU = \frac{(HU_{\text{Max}} - HU_{\text{Min}})}{1000} \times 100$$

The spatial resolution was measured using the CTP528 module which has 21 line pair (lp) cm⁻¹ gauges cut from 2-mm thick aluminum sheets and cast into epoxy. Since, our aim was to have a head to head comparison of the MV scatter effect between the full and half arc; we used the same Catphan (without annulus) for both the measurements. In case one intends to use a different scattering medium, then the MV scatter effect would be different.

RESULTS AND DISCUSSION

The purpose of this work was to evaluate the impact of MV scatter on the image quality of CBCT scans which were acquired concurrent with arc delivery. This evaluation was carried out for different photon beams (6 and 15 MV), arc types (half and full arc), static field sizes (10 × 10 and 25 × 25 cm²) and SIDs (150 and 170 cm). The CBCT image quality was compared with that of the reference CBCT scans (without MV beam on).

Table 1 shows the HU, CNR, SNU and spatial resolution values observed at a SID of 150 cm. From this table, it is observed that the HU accuracy, CNR and SNU were considerably affected by MV scatter, and this effect was increased with increasing treatment field sizes and decreasing MV photon energy. Figure 1a–e shows the cupping effect of MV scatter for 6- and 15-MV full-arc treatments, and it is evident that this effect was higher for 6-MV photon beam than for 15-MV photon beam. When comparing this effect between half- and full-arc treatments, it was found to be high for the full-arc treatment; Figure 2a,b shows the head to head comparison between half- and full-arc deliveries. Table 2 shows the image quality of CBCT acquired at a SID of 170 cm. It can be observed that increasing the SID from the nominal distance of 150 to 170 cm resulted in a decreased MV scatter effect, and this improved the CBCT image quality. Similarly, Figure 3a,b reveals that the cupping effect owing to MV scatter was reduced at a 170-cm SID.

The loss of image quality observed for the CBCT images that were acquired during MV beam on was attributable to increased photon scatter that reached the imager. As can be seen from Table 1, the MV scatter effect that was observed is maximum for CBCT scans acquired at a SID of 150 cm for 6-MV full-arc plans with a treatment field size of 25 × 25 cm². Because, the scatter

Figure 3. Reconstructed slices of Catphan® 600 (The Phantom Laboratory Inc., Salem, NY) acquired during 6-MV full arc [half-fan cone beam CT (CBCT) mode] treatments with a field size of $25 \times 25 \text{ cm}^2$. (a) Images of 150-cm source-to-imager distance (SID); (b) images of 170-cm SID. All images are shown with the same window width and level. The cupping effect was considerably reduced at a SID of 170 cm.

photons that reach the imager are more for this combination. The maximum deviation observed for HU and SNU was $160 \pm 145\%$ (average of seven sensitometry targets) and 8.3%, respectively. Similarly, the CNR was decreased by a factor of two. Unlike other parameters, the spatial resolution was not affected much (Tables 1 and 2).

Furthermore, increasing the SID to 170 cm decreased the number of scatter photons reaching the detector and hence improved the image quality. Increasing the SID is a practical method for reducing MV scatter, but it may not completely remove the MV scatter effect. Hence, appropriate scatter correction techniques should be utilized for reducing MV scatter, and recently, various methods have been reported.^{15–17} Ling et al¹⁵ developed a method to acquire MV-scatter-free kV CBCT images simultaneous with the delivery of RapidArc® treatment. In this method, each control point in RapidArc was divided into two, with the first control point for MV beam delivery and the second control point for acquiring kV image acquisition. During the imaging control point, the MV beam was turned off for eliminating the MV scatter in kV projection. kV projections that had minimal MV scatter were selected based on the gantry angle, and the CBCT images were reconstructed. This method

resulted in a CBCT image quality similar to that of the reference scans. In another technique, van Herk et al¹⁶ developed a novel method for MV scatter correction in CBCT acquired during volumetric modulated arc therapy delivery. During acquisition, the kV imaging system acquired alternating pulse sequence with the even frames contained a kV image combined with MV scatter, and the odd frames (no kV pulse is generated) only contained MV scatter plus a surplus amount of image lag from the previous frame. MV-scatter-free CBCT images were obtained by subtracting the even frames from the odd frames. Alternatively, the kV imaging parameters can also be adjusted for maintaining sufficient image quality with reduced imaging dose.²² Recently, Wallace et al²² thoroughly investigated the image quality of a KIM system which uses kV imaging during the treatment for real-time tracking of prostate fiducial markers. They included a range of parameters such as kV acquisition frame rates, kV exposure conditions, MV dose rate and patient sizes. They recommend using the kV parameters of 5 Hz at 1 mAs, which could reduce the dose while maintaining the image quality for a maximum patient dimension of $<36.4 \text{ cm}$.

The following point needs to be considered when interpreting the results. In this study, the MV scatter effect in open beam was investigated, whereas the scatter effect would be different in intensity-modulated arc deliveries and hence a separate study is required for this evaluation. Finally, this work may be beneficial to physicists for a better understanding of the MV scatter effect on kV CBCT image quality acquired during arc delivery, and also it instigates additional issues for future investigation.

CONCLUSION

In this study, image quality of kV CBCT acquired during the delivery of arc treatments was evaluated. MV scatter considerably affected CBCT image quality, and this effect increased for increasing field size and decreasing MV photon energy. The MV scatter effect was higher in half-arc than in full-arc treatment. In addition, the MV scatter effect can be considerably reduced by increasing the SID.

FUNDING

This work was supported by the Department of Science and Technology, the Government of India, grant no: IR/SO/LS 02/2003.

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