PERFORMANCE CHARACTERISTICS AND QUALITY ASSURANCE ASPECTS OF KILOVOLTAGE CONE-BEAM CT ON MEDICAL LINEAR ACCELERATOR

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Abstract—A medical linear accelerator equipped with optical position tracking, ultrasound imaging, portal imaging, and radiographic imaging systems was installed at University of Pittsburgh Cancer Institute for the purpose of performing image-guided radiation therapy (IGRT) and image-guided radiosurgery (IGRS) in October 2005. We report the performance characteristics and quality assurance aspects of the kilovoltage cone-beam computed tomography (kV-CBCT) technique. This radiographic imaging system consists of a kilovoltage source and a large-area flat panel amorphous silicon detector mounted on the gantry of the medical linear accelerator via controlled arms. The performance characteristics and quality assurance aspects of this kV-CBCT technique involves alignment of the kilovoltage imaging system to the isocenter of the medical linear accelerator and assessment of (a) image contrast, (b) spatial accuracy of the images, (c) image uniformity, and (d) computed tomography (CT)-to-electron density conversion relationship were investigated. Using the image-guided tools, the alignment of the radiographic imaging system was assessed to be within a millimeter. The low-contrast resolution was found to be a 6-mm diameter hole at 1% contrast level and high-contrast resolution at 9 line pairs per centimeter. The spatial accuracy (50 mm ± 1%), slice thickness (2.5 mm and 5.0 mm ± 5%), and image uniformity (± 20 HU) were found to be within the manufacturer’s specifications. The CT-to-electron density relationship was also determined. By using well-designed procedures and phantom, the number of parameter checks for quality assurance of the IGRT system can be carried out in a relatively short time.

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Key Words: One-beam CT, Radiosurgery, IGRT, Image quality, Quality assurance.

INTRODUCTION

The recent implementation of the state-of-art radiation therapy technology in dose planning and dose delivery has led to the wide spread practice of 3-dimensional conformal radiation therapy (3D-CRT) and, in particular, intensity modulated radiation therapy (IMRT).1–6 These newly introduced treatment techniques require precise location and clear delineation of targets and surrounding normal critical structures. In addition, the 3D shape of both the targets and critical structures must be clearly delineated for the generation of well-designed treatment plans for patients undergoing 3DCRT. In the practice of 3DCRT, the field of each radiation beam is shaped using cerrobend blocks or multileaf collimation (MLC) system based on the beam projection onto the target (beam’s-eye view). The field outline is drawn to just cover the target plus a margin. On the other hand, IMRT treatment plans are designed with the intent to yield dose distributions that are highly conformal to the target volumes, in particular, those targets with concave or irregular shapes and steep dose gradient, to minimize the irradiation of surrounding normal tissues. This IMRT treatment technique is an extension of 3D CRT technique with the inclusion of intensity modulation capability across the radiation field. Although the field outline is no longer critical, the delivery of the radiation dose to the target volumes must also be very precise and accurate as well. In both treatment techniques, the targets and relative surrounding critical tissues must be in the static state and repeated positioning would yield almost the same coordinates except where motion-gating technique is implemented.7–9 The need for this higher degree of precision and accuracy has lead to the emergence of image-guided radiation therapy (IGRT) technologies.

The current trend of IGRT has been directed at devising more precise and accurate methods of radiation dose delivery to the target sites. These stringent requirements of IMRT for a higher degree of accuracy for target positioning and higher degree of precision in physical dimensional shapes of the targets and critical structures determination have lead to the extensive development of a number of positioning and/or tracking techniques.
These techniques include the radiographic imaging of fiducial markers, ultrasound-based imaging of anatomy, detection of beacon to determine locations, video-based surface tracking, in-room CT imaging, megavoltage cone-beam CT (MV-CBCT) imaging, and kilovoltage cone-beam CT (kV-CBCT) imaging. This newly acquired information must be correlated to the patient position setup in the treatment plan for localization and verification at the treatment machines. We report the performance characteristics and quality assurance aspects of our newly commissioned linear accelerator with kV-CBCT capability for performing image-guided radiation therapy (IGRT) and image-guided radiosurgery (IGRS).

**METHODS AND MATERIALS**

A Varian linear accelerator model Trilogy was installed at University of Pittsburgh Cancer Institute–Shadyside Campus for the purpose of performing IGRT and IGRS in October 2005. The linear accelerator has 2 photon beams with accelerating potentials of 6 MV and 23 MV and 5 electron beam energies from 4 to 20 MeV. In the stereotactic mode, the linear accelerator uses the 6-MV photon beam with modified flattening filter to deliver a dose rate of 1000 monitor units (MUs) per minute. The collimator can be open up to a maximum field size of $15 \times 15$ cm and delivers up to 60 MU per degree arc in this mode. The linear accelerator is equipped with the Millennium MLC-120 multileaf collimator system with 60 leaves on each of the 2 banks. The 20 outer leaves from the beam axis have a projected leaf width of 1.0 cm, and 40 inner leaves with 0.5-cm projected leaf width at the isocenter. The stated average leaf transmission in the vendor specification is less than 2.5% and the maximum interleaf leakage is less than 4%.

The additional stereotactic components consist of the (a) Zmed conical collimators for stereotactic radiosurgery (SRS) treatments, (b) head ring and couch mount for single fraction radiosurgical treatments, (c) head and neck immobilization for multifraction stereotactic radiotherapy treatments, (d) CT localizer, (e) stereotactic treatment planning system, and (f) optical position tracking system.

Along with the optical position tracking system, the linear accelerator is also equipped with an ultrasound imaging, portal imaging, and on-board radiographic imaging systems. The ultrasound imaging system is placed on a dedicated cart that can be moved within the room and away from the gantry. On the other hand, the on-board imager consists of a kilovoltage (kV) x-ray source and a large-area flat panel amorphous silicon (aSi) detector mounted onto the gantry of the linear accelerator via controlled arms. The on-board imager can be retracted and stored out of the way when not in use. The on-board imager operates in a direction that is orthogonal to the megavoltage beam direction, as shown in Fig. 1.

The megavoltage beam and the electronic portal-imaging device (EPID) can be used with the on-board imager to take orthogonal images without rotating the gantry. However, their image quality is expected to be different due to the type of photon interactions involved.

The IGRT capability of this linear accelerator includes the ability to perform kilovoltage cone-beam computed tomography (kV-CBCT). In this technique, the entire volumetric data is acquired by performing a single gantry rotation around the patient with the kilovoltage source energized covering a size of 50 cm in diameter and 17-cm long. The transaxial images are reconstructed after the projection data are acquired. The kV-CBCT technique offers the advantage of soft tissue visualization for target localization at the time of patient treatment. This is particularly important in the treatment of prostate or small target without fiducial markers. The kV-CBCT images can also be exported to the treatment planning system for performing image fusion and thereafter the calculation of overall effective dose distribution over a number of fractions.

The method of acquiring kV-CBCT images is very different from the typical CT images. In kV-CBCT technique, the data are acquired volumetrically with the inclusion of radiation scatter. As such, there has been investigation to examine the effect and magnitude of the scatter component. The source-to-detector distance is also further, at 150 cm compared to a conventional CT or CT-simulation scanner.

Because the on-board imager is a newly added hardware mounted onto the medical linear accelerator, quality assurance to ensure precise alignment and stability is crucial. First, the on-board imager should be accurately aligned to isocenter of the linear accelerator. Additionally, the optical position tracking system is also calibrated to the same isocenter of the linear accelerator. Any deviation or shift relative to the isocenter is recorded in the optical position tracking system and also the on-boarding imaging system.
The quality assurance aspects involve the scanning of the CT localizer, transferring the CT images to the treatment planning system, and then creating two orthogonal digital reconstructed radiographs (DRR). These 2 orthogonal DRRs are then downloaded to the medical linear accelerator for comparison or fusion. In the treatment room, a mechanical front pointer is used to physically locate the isocenter and identified using a radiopaque ball fixed to an optically monitored device (Fig. 2). A set of orthogonal diagnostic radiographs is taken using the on-board imager and electronically compared to the DRRs. The comparison can be made manually by fusing the images or performed by the software automatically (Fig. 3). Next, the radiopaque ball is intentionally moved to a specified distance away from the isocenter in 3 dimensions using the treatment couch. Another set of orthogonal diagnostic radiographs of the radiopaque ball is taken using the on-board imager. These radiographs are again fused to the DRR manually or automatically using the software. If the radiopaque ball is properly aligned between the radiographs and the DRRs, there is a request for shifting the treatment couch by the exact distance of initial displacement.

The intended use of the kV-CBCT system, as emphasized by the vendor, is to extract soft tissue visualization for patient positioning.15,18 As such, the quality of the kV-CBCT images must be assessed and regularly monitored. The image quality was assessed by scanning the Catphan Model 500 phantom (Fig. 4). The phantom provided by the vendor is hinged over the open box, as shown in the figure, and extended beyond the treatment couch to avoid couch interference. Precaution should be taken to make sure that the open box is stable and is adequately counterweight to prevent tipping. The phantom is then aligned close to the isocenter of the linear accelerator. The phantom is scanned and transaxial images are reconstructed using 2.5-mm-slice thickness. The transaxial images of this phantom will reveal the performance characteristics of the system that include (a) image contrast, (b) spatial accuracy, (c) image uniformity, (d) reconstruction slice thickness, and (e) CT-to-electron density relationship.

**RESULTS**

The quality assurance on the on-board imager assumes that the mechanical isocenter and megavoltage radiation isocenter of the medical linear accelerator has

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**Fig. 2.** Radiopaque ball mounted onto an optical position tracking device and position at isocenter.

**Fig. 3.** Display of the DRR and radiograph taken using the on-board imager for fusion.
already been established and the physical location in space has been identified using the mechanical front pointer. The quality assurance checks the alignment of the on-board imager by referencing to the isocenter of the medical linear accelerator using the IGRT tools. When the radiopaque ball was positioned at the isocenter, the orthogonal radiographs taken using the on-board imager and fused to the DRRs showed the shifts were within 1 mm. The spatial accuracy was checked with the radiopaque ball moved away from the isocenter by known distances in 3 dimensions. The image fusion requested the same amount to be shifted back to within 1 mm in all 3 spatial directions. The above quality assurance was extended to check the optical position tracking system for proper functional performance.

The image quality of the kV-CBCT specification is summarized in Table 1. For low-contrast resolution, the fifth largest hole was visible (Fig. 5). This hole has a dimension of 6-mm diameter with 1.0% contrast level. For high-contrast resolution, the 9 line pairs per centimeter corresponding to a gap size of 0.056 cm were observed with separation (Fig. 6). The gauge was made with 2-mm-thick aluminium and cased into epoxy. The manufacturer’s specification is 6 line pairs per centimeter, corresponding to a gap size of 0.083 cm. The spatial accuracy was determined in the transaxial image by measuring designed

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Low-contrast resolution</td>
<td></td>
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<tr>
<td>1.0% contrast hole</td>
<td>7-mm diameter</td>
</tr>
<tr>
<td>High-contrast resolution</td>
<td></td>
</tr>
<tr>
<td>Line pairs per cm</td>
<td>6 lp/cm</td>
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<tr>
<td>Spatial accuracy</td>
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<td>50-mm distance</td>
<td>50 mm ± 1%</td>
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<tr>
<td>Image uniformity</td>
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<td>Water</td>
<td>± 20 HU</td>
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<tr>
<td>Slice distance</td>
<td></td>
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<tr>
<td>2.5 and 5.0 mm</td>
<td>± 5%</td>
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<tr>
<td>Density resolution</td>
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<tr>
<td>PMP</td>
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<tr>
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<td>Delrin</td>
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<tr>
<td>Teflon</td>
<td>990 HU</td>
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Fig. 4. A Catphan Model 500 phantom that allows the assessment of image quality of kV-CBCT images.

Fig. 5. A kV-CBCT transaxial image showing low-contrast resolution.

Fig. 6. A kV-CBCT transaxial image showing high-contrast resolution.
points (Fig. 7). The separation between nearest points is 5 mm in a square shape. As listed in Table 1, the expected spatial accuracy is to be within 1%. It should be noted that the reconstructed slice thickness is selected to be 2.5 mm. After image reconstruction, the slice thickness can be determined from the presentation given in Fig. 8 as one of the axial images.

The image uniformity was evaluated by measuring selected regions on the transaxial image through the water region of the phantom. Five regions of interest were located on the major axes and one region at the center of the image. All values were found to be within the manufacturer specification of 0 ± 20 HU.

DISCUSSION

Although the rationales for the introduction of several positioning and imaging systems are clear, their actual usability is not firmly established. Which system will become obsolete and which system will become popular or useful remains to be seen. It is quite understandable that there are overlaps of usage between systems, for example, both ultrasound-based and fiducial-based systems are very useful for localizing the prostate. It is also quite clear that some IGRT systems can be use for patient positioning for a number of anatomical sites. As the experience with IGRT increases, which system becomes better suited for IGRT will become clearer.

As radiation therapy technology advances, the equipment becomes more sophisticated and thereby adding another level of complexity to the operation and quality assurance of medical linear accelerator. Currently, medical linear accelerators incorporate IGRT devices such as ultrasound imaging system, optical position tracking system, and radiographic imaging system, in addition to portal imaging system. Correspondingly, the number of parameters that must be checked as part of quality assurance also increases significantly. It is prudent to find a procedure or a device that would incorporate as many parameter checks as possible to determine the performance characteristics of the equipment to alleviate the burden on quality assurance responsibilities.

The CT-to-electron density relationship was determined by defining region of interests on the inserts shown in Fig. 7. The CT numbers range from −1000 HU to +1000 HU and cover the physical density from 0.0 (air) to 2.16 g/cm³ (Teflon). All CT numbers were within the manufacturer’s specifications. The relationship of the CT-to-electron density for kV-CBCT images is shown in Fig. 9.
The comparison of the radiographic images from the on-board imager to the DRR has in fact integrated a number of parameter checks into a single procedure. This procedure checks (a) the reference point of the optical position tracking system, (b) the calibration of the imaging system, (c) movement of the treatment couch, (d) displacement in the optical position tracking system, and also the spatial information in the treatment planning system. The latter 3 performance characteristics were checked based on the displacement of the radiopaque ball by known distances. Clearly integrated procedure or phantom would assist in quality assurance.

The phantom with the integration of multiple sections has offered a device to check multiple parameters in a single procedure. This phantom allows the check of image quality, spatial accuracy, image uniformity, and also CT-to-electron density.

Because kV-CBCT is a newly introduced product, data on the number of parameters in the quality assurance and the frequency of performing these checks are limited. Islam et al. had performed exposure measurement on a different kV-CBCT unit and found that the exposure dose to be in the range of 1 to 4 cGy for various combinations of phantom size and scanning parameters. Some deduction can also be made from past experiences on other similar modality, such as the CT simulator. Regarding checking the alignment of imaging plane, AAPM Task Group 66 recommended that this procedure be done daily on CT-simulator scanner. It may be reasonable that the alignment check be also performed daily on the kV-CBCT scanner as well. The alignment check as described also check on the integrity of the optical position tracking system and the correspondence of the table movement. The laser alignment check with the imaging plane is inherently a part of the quality assurance for the medical linear accelerator because all alignment is reference to the isocenter of the medical linear accelerator. The CT number is checked daily for water and a few materials monthly followed by tissue characterization annually. The field uniformity for the commonly used scanning setting is checked monthly and other type of setting be checked annually. Spatial resolution and contrast resolution are checked annually. Although the AAPM Task Group 66 recommended the above quality assurance frequency for CT-simulator, it may be applicable to kV-CBCT scanner until firm data become available. At our institution, the on-imager alignment is checked daily and image quality is assessed monthly.

The incorporation of an IGRT system; in particular, radiographic imaging system, to a medical linear accelerator provides a tool to delineate the target for localization prior to patient treatment. The implementation of kV-CBCT technique is particularly favorable because anatomical structures and soft tissues are better visualized on transaxial images than planar images. This kV-CBCT technique, if successful, would provide the ability to perform adaptive radiation therapy where the dose distribution can be computed promptly to conform to current target location and shape change prior to patient treatment.

REFERENCES