A Study on Evaluation of kV-CBCT-image-based Treatment Planning using Anthropomorphic Phantom

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Abstract

Kilovoltage cone-beam computed tomography (kV-CBCT) based on flat-panel technology is primarily used for patient positioning. It can also be used for re-planning and dosimetric verification in adaptive radiotherapy by validating the accuracy of CBCT-image-based treatment planning. This study evaluates the accuracy of dose calculation based on CBCT images using an anthropomorphic phantom. The Hounsfield unit (HU) – electron density calibration curves for full-fan and half-fan modes of CBCT are obtained using a Catphan® 600 phantom and compared with the conventional CT curve. The stability of the CBCT calibration curve with time is also studied over a period of 8 weeks. CT and half-fan CBCT imaging of the anthropomorphic phantom was obtained. The isodose distributions of a single direct field and wedge fields are compared for CT- and CBCT-image-based dose calculations. Simulated identical targets and organs at risk are delineated in CT and CBCT images for which conformal radiation therapy (CRT) and intensity-modulated radiation therapy (IMRT) plans were generated. The percentage dose differences and dose-volume histograms (DVHs) of CT- and CBCT-based plans are compared. It is found that the maximum difference in HU between half-fan CBCT and CT is -40 HU. No significant change is observed in the calibration curves over a period of 8 weeks. The isodose distributions computed based on CBCT and CT for a single direct field and wedge fields agrees to within 1%. For head and neck and pelvis IMRT plans, the dose calculated using CT agrees with that of CBCT-based calculation to within ±1.0%, respectively. However, for the thorax, there is a pronounced discrepancy at the 100% isodose line and the dose difference is within ±3%. It can be thus concluded that CBCT images can be used for dose calculation, but it is necessary to validate the dosimetric data for inhomogeneous tissue regions.

Keywords: Cone-beam computed tomography (CBCT), Dose calculation, Rando phantom

1. Introduction

Recent developments in image-guided radiation therapy (IGRT) have provided tools for improving patient positioning and target localization accuracy. Kilovoltage cone-beam computed tomography (kV-CBCT) integrated into a linear accelerator was developed to acquire online anatomical and volumetric images [1]. By matching soft tissues and/or bony structures in the CBCT to those in planning CT images, patient positioning can be verified accurately. In addition, to guide the patient setup, the CBCT data acquired prior to treatment can be used to recalculate and verify the treatment plan based on the patient anatomy on the day of treatment [2-6]. This allows the patient’s treatment plan to be adaptively modified during the radiation therapy course based on the dose that has already been delivered. However, this application depends on the CBCT image quality.

Unlike conventional CT, kV-CBCT covers a much larger field of view (FOV) in the longitudinal direction. Scatter is thus a more severe problem in the resultant image. Since the gantry rotation speed is limited to ~1 rotation per minute by International Electrotechnical Commission regulations, CBCT is prone to motion artifacts. Our previous study found that non-gated CBCT imaging of moving targets can lead to significant loss of volumetric information but a lesser distortion of shape [7]. Poor image quality raises serious concerns about the dosimetric reliability of CBCT-based dose calculations. This study evaluates the dosimetric accuracy of kV-CBCT-based dose calculation using an anthropomorphic phantom (Rando phantom) for the head and neck, thoracic, and pelvic sites.

2. Materials and methods

2.1 Image acquisition

The on-board imager (OBI) integrated into the Varian Clinac 2100C/D linear accelerator (Varian Medical Systems,
The calibration of a CT scanner involves acquiring CT images, obtaining an average HU for each inserted material, and plotting the HU values as a function of the relative electron density. The calibration curve was obtained for CT images in a fan mode, the beam central axis passes through the detector center and a full projection of the scanned patient is acquired for each angle. This acquisition mode produces an FOV (field of view) of about 25.5 cm in diameter and 17 cm in the axial length. The half-fan mode is designed to obtain a larger FOV. In this mode, the detector is shifted laterally to take only half of the projection of the scanned patient for each angle. This acquisition mode produces an FOV of about 45 cm in diameter and 15 cm in the axial length. A bowtie filter was mounted on the X-ray tube to improve image quality. For imaging, the default parameters, defined during calibration, were 120 kVp, 80 mA, and 25 ms.

A GE lightspeed CT simulator (GE Medical Systems, Milwaukee, WI) was used for acquiring CT images with a 2-mm slice thickness. 120 kVp and an automatically adjusted current were used.

2.2 Calibration of CT and CBCT

To use a CT or CBCT image for dose calculation, the Hounsfeld unit (HU) of the scanner must be related to the actual electron density. A CT phantom, Catphan® 600 was used. The Catphan® 600 has a diameter of 15 cm (longitudinal dimension is 16 cm) and contains seven tissue substitute materials, namely air, poly-methyl pentene (PMP), low-density polyethylene (LDPE), polystyrene, acrylic, delrin, and teflon. Their relative electron densities relative to water range from 0 to 1.867.

The calibration of a CT scanner involves acquiring CT images, obtaining an average HU for each inserted material, and plotting the HU values as a function of the relative electron density. The calibration curve was obtained for CBCT in full-fan and half-fan modes. The calibration curves of the CT, full-fan CBCT, and half-fan CBCT images were compared. Cross-sectional images of the phantom imaged with the CT, full-fan CBCT, and half-fan CBCT are shown in Fig. 1. The stability of CBCT calibration curve with time was also studied over a period of 8 weeks by scanning the phantom weekly. The HU – relative electron density curves obtained weekly were then compared to assess the HU fluctuations with time.

![Figure 1](image.png)

Figure 1. Cross-sectional images of Catphan® 600 phantom obtained using (a) CT, (b) full-fan CBCT, and (c) half-fan CBCT.

The CT, full-fan CBCT, and half-fan CBCT images of the Catphan® 600 phantom were imported into the Eclipse treatment planning system (Varian Medical Systems, Palo Alto, CA). The HU distribution over homogeneous and inhomogeneous media of the phantom was analyzed to quantify the differences in the image quality of CT and CBCT. To assess the effect of radial scatter, three homogeneous phantoms with radial diameters of 10, 20, and 27 cm, respectively, were scanned using CBCT.

2.3 CBCT-image-based planning

2.3.1 Isodose comparison: single direct field and wedge fields

For planning and evaluation purposes, a single direct 10 x 10 cm², 6-MV photon beam isocentered at the center of the Catphan® 600 phantom was generated for the CT, full-fan CBCT, and half-fan CBCT images. Anisotropic analytical algorithm (AAA)-based dose calculation was used and the conventional CT electron density calibration curve was applied for all the images. The resultant isodose curves and the dose profiles at 1.5, 5, 10, and 15 cm depths were obtained and compared. Similarly, four wedge fields (with angles of 15°, 30°, 45°, and 60°) of 6-MV photon beams at gantry angles of 0°, 90°, 180°, and 270° isocentered at the center of the phantom were generated for the CT and CBCT images. The isodose curves and dose profiles were obtained and compared.

2.3.2 Intensity-modulated radiation therapy (IMRT) dose comparison

A detailed study using a Rando phantom was performed to validate CBCT-based dose calculation. Three sites, namely the head and neck, the thorax, and the pelvis, were used for the study. The CT and half-fan CBCT images of the phantom were obtained. For all sites, a hypothetical identical target and sensitive structures were contoured on CT and CBCT image sets.

For the pelvis CT, an IMRT plan with five 6-MV photon fields, at gantry angles of 0°, 55°, 100°, 260°, and 305°, respectively, was generated. A verification plan was created based on CBCT images, keeping the MU values and fluence maps of the original CT-based plan. The resultant dose distributions and dose-volume histograms (DVHs) of the CT- and CBCT-based plans were compared.

Similarly, for the head and neck CT, an IMRT plan with seven 6-MV photon fields, at gantry angles of 0°, 50°, 100°, 150°, 310°, 260°, and 210°, respectively, was generated. For the thorax CT, an IMRT plan with four 6-MV photon fields, at gantry angles of 0°, 110°, 180°, and 250°, respectively, was generated. Their corresponding verification plans were created with the CBCT images. The resultant dose distributions and DVHs of the corresponding plans were compared.

2.3.3 Build-up region dose comparison

In order to verify the build-up region dose distribution, at the thoracic site, a superficial target was contoured. A three-dimensional conformal plan using three 6-MV photon fields, at gantry angles of 0°, 60°, and 360°, respectively, (lateral fields with a 15° wedge) was generated. A similar plan was created with the CBCT images. The dose distributions of CT- and CBCT-image-based plans for the superficial target were compared.
3. Results

3.1 Calibration of CT and CBCT

The HU versus relative electron density calibration curves of the conventional CT, full-fan CBCT, and half-fan CBCT are shown in Fig. 2. In the full-fan mode, the maximum difference in the HU value compared with the reference CT is less than 20 HU. For the half-fan mode, HU values of tissue substitute materials were slightly higher than those of CT and teflon showed the maximum HU difference (40 HU). This study confirms that CBCT has the ability to generate images with HU values comparable to those of CT.

Figure 2 shows the calibration curves (CT number versus relative electron density) for CT, full-fan CBCT, and half-fan CBCT.

Figure 3 shows the calibration curves obtained in eight consecutive weeks for the full-fan CBCT. No significant variation was observed in the calibration curve, confirming the stability of kV-CBCT with time for HU value integrity.

Figure 3. Stability of calibration curve over a period of 8 weeks for full-fan CBCT.

Figure 4 shows the HU profiles in homogeneous and inhomogeneous media obtained from CT, full-fan CBCT, and half-fan CBCT images of the Catphan® 600 phantom. It is found that the HU profiles of the CT and full-fan CBCT normally agree to within difference of 10 HU except the peripheral region where it is reduced by 10 to 40 HU. The HU profiles of half-fan CBCT were 10 to 30 HU higher along the central region and 30 to 80 HU lower at the periphery when compared to the CT profiles.

Figure 4. HU profiles along homogeneous and inhomogeneous media from CT, full-fan CBCT, and half-fan CBCT images of Catphan® 600 phantom.

Figure 5 shows the HU profiles along a central axis of three homogeneous water equivalent phantoms of various sizes. As expected, the fluctuation range of HU values increases with the phantom diameter, indicating the increased influence of scatter radiation.

Figure 5. HU profiles for homogeneous water equivalent phantoms with diameters of 27, 20, and 10 cm, respectively.

3.2 CBCT-based planning

Figure 6(a) shows the dose distributions calculated using a single direct 10 × 10 cm² 6-MV photon beam in the transverse section of three respective sets of images. Figure 6(b) shows a comparison of dose profiles at depths of 1.5, 5, 10, and 15 cm. From this analysis, the dose calculated using CT agrees with the CBCT-based dose calculation to within 1%. Figure 7(a) shows the dose distribution calculated using wedge fields in the transverse section of the three sets of images. Figure 7(b) shows a comparison of dose profiles along the orthogonal beam central axis. The CT-image-based dose calculation agrees with that of CBCT to within 1%.
Figure 6. (a) Dose distributions calculated using a single direct $10 \times 10$ cm$^2$ 6-MV photon beam in the transverse section of three respective sets of images of (i) CT, (ii) full-fan CBCT (FFCBCT), and (iii) half-fan CBCT (HFCBCT). (b) Comparison of dose profiles at depths of 1.5, 5, 10, and 15 cm.

Figure 7. (a) Dose distributions calculated using wedge fields in the transverse section of three sets of images of (i) CT, (ii) full-fan CBCT (FFCBCT), and (iii) half-fan CBCT (HFCBCT). (b) Comparison of dose profiles along the orthogonal beam central axis.
CBCT-image-based Dose Calculation

Figure 8. (a) IMRT dose distributions computed based on CT and CBCT pelvic images. (b) Comparison of DVHs of the target and sensitive structures. (c) Percentage dose difference computed based on Verisoft 3.1 software. Solid and dotted curves represent the results from CT- and CBCT-based calculations, respectively.

Figure 9. (a) IMRT dose distributions computed based on CT and CBCT head and neck images. (b) Comparison of DVHs of the target and sensitive structures. (c) Percentage dose difference computed based on Verisoft 3.1 software. Solid and dotted curves represent the results from CT- and CBCT-based calculations, respectively.
Figures 8(a) to (c) compare the IMRT dose distributions computed based on the CT and CBCT images in the pelvic region of the Rando phantom. The DVHs of the target and sensitive structures are also presented. The resultant percentage dose difference was calculated using Verisoft 3.1 software. The dose calculated using CT agrees with the CBCT-based dose calculation to within ±1%.

Figures 9 and 10 compare IMRT dose distributions computed based on CT and CBCT images in the head and neck site and the thorax site of the Rando phantom, respectively, along with the respective DVHs of the target and sensitive structures. For the head and neck site, the percentage dose difference was found to be within ±1%. For the thorax site, the percentage dose difference was found to be within ±3%, which is clinically significant. For both cases, the doses showed good agreement between 30% and 90% isodose lines, but there were discrepancies at the 100% isodose line, with that for the thorax IMRT case more pronounced.

A dose comparison of CT- and CBCT-based planning of a superficial target is shown in Fig. 11. The dose calculated using CT agrees with the CBCT-based calculation to within ±1%.
4. Discussion

CBCT based on flat-panel technology integrated in a medical linear accelerator has improved the precision of targeting in radiotherapy. Two important applications of CBCT are patient setup and dose verification. A CBCT image of the patient on the treatment table can be acquired in about 60 seconds, just before delivery of each treatment. These pretreatment volumetric images may be used to verify or correct the patient setup and recalculate the treatment plan based on patient anatomy on treatment day. However, this application depends on the CBCT image quality. The quality of CBCT images is inferior to that of conventional CT images due to increased scatter, beam hardening, and intra-scanning organ motion. This raises concerns about the direct use of CBCT for dose calculation [8]. This study investigated the accuracy of CBCT-based treatment planning using a Rando phantom for head and neck, thorax, and pelvis sites.

Results show that the difference in HU values between CT and CBCT images of Catphan® 600 phantom are less than 40 HU. Teflon shows the maximum variation in the half-fan mode. There was no significant change in the HU – electron density curve over a period of eight weeks. Thus, this study confirms that CBCT has the ability to generate images with HU values comparable to those of CT.

The profiles of full-fan CBCT in a homogeneous medium were 10 to 40 HU lower at the periphery region when compared to those of CT. For half-fan CBCT, the HU profiles were 10 to 30 HU higher and 30 to 80 HU lower along the central and peripheral regions, respectively, when compared to profiles of CT. This reduction in HU at the periphery may be due to larger primary-to-scatter ratio with a larger FOV.

The influence of HU variation in dose calculation was evaluated by comparing the dose distribution and DVHs between CT- and CBCT-image-based treatment planning. The dose distributions calculated for a single direct 10 × 10 cm² 6-MV photon beam for CBCT images of Catphan® 600 phantom agrees with that of CT to within 1%. Similarly, the dose distribution calculated with wedge fields for CBCT images agrees with that of CT to within 1%.

In general, IMRT plans based on CBCT images for the head and neck and pelvis sites of the Rando phantom show a good agreement with the plans based on CT. However, for the thorax site, a discrepancy at the 100% isodose line was noted and the percentage dose difference was found to be within ± 3%. For the 3D-CRT plan for a superficial target, the percentage dose difference was found to be within 1%.

Although the results of CBCT-based plans provided in this study are comparable to those of CT-based plans, for larger treatment volumes, CBCT-based planning could be limited due to the limited field size of the detector (about 16 cm in length). However, CBCT-based planning can be useful for re-planning purposes to provide monitor units and dose distribution or to verify treatment delivery.

5. Conclusions

Cone-beam CT plays an important role in modern radiotherapy in terms of accurate patient setup and dose verification. This study investigated the dosimetric feasibility of CBCT-based treatment planning using a Rando phantom. Although CBCT images include larger scatter and artifacts than do CT images, the dosimetric results of CBCT-based plans are comparable to those of CT-based plans. Dosimetric data in inhomogeneous tissue regions such as the thorax region should be carefully validated.

References
