Integration of Cone-Beam CT in Stereotactic Body Radiation Therapy

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This report describes the technique and initial experience using cone beam CT (CBCT) for localization of treatment targets in patients undergoing stereotactic body radiation therapy (SBRT). Patients selected for SBRT underwent 3-D or 4-D CT scans in a customized immobilization cradle. GTV, CTV, ITV, and PTV were defined. Intensity-modulated radiation beams, multiple 3-D conformal beams, or dynamic conformal arcs were delivered using a Varian 21EX with 120-leaf MLC. CBCT images were obtained prior to each fraction, and registered to the planning CT by using soft tissue and bony structures to assure accurate isocenter localization. Patients were repositioned for treatment based on the CBCT images. Radiographic images (kV, MV, or CBCT) were taken before and after beam delivery to further assess set-up accuracy. Ten patients with lung, liver, and spine lesions received 29 fractions of treatment using this technique. The prescription doses ranged 1250 ~ 6000 cGy in 1 ~ 5 fractions. Compared to traditional 2-D matching using bony structures, CBCT corrects target deviation from 1 mm to 15 mm, with an average of 5 mm. Comparison of pre-treatment to post-treatment radiographic images demonstrated an average 2 mm deviation (ranging from 0-4 mm). Improved immobilization may enhance positioning accuracy. Typical total “in-room” times for the patients are approximately 1 hour. CBCT-guided SBRT is feasible and enhances setup accuracy using 3-D anatomical information.

Key words: Cone-beam CT; Image-guided radiation therapy; Stereotactic body radiation therapy; Extracranial radiosurgery; and Hypofractionation.

Introduction

The backbone of conformal radiation therapy is the accurate application of radiation dose to the target. This is especially true for radiosurgery/hypofractionated techniques, since the margins are typically small and the doses are high. Several recent clinical studies report encouraging results with hypofractionated stereotactic body radiation therapy (1-13).

One key to the successful implementation of hypofractionated treatment is accurate target localization. Small margins are needed to minimize the volume of normal tissue irradiated given the high doses of radiation employed. Over the past several years, image-guided techniques have evolved permitting accurate target localization. Many of these techniques use planar kV and MV imaging. Two dimensional images may be helpful for patients with tumors having a fixed position relative to bony structures, i.e., if the tumor target and bony landmarks are rigidly connected, or when implanted radio-opaque fiducials are used. Such 2D imaging methods may not be adequate for soft-tissue targets.

Accurate 3-D anatomy of the patient on the linear accelerator is often preferable.

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A diagnostic CT unit in the RT treatment room (e.g., “CT on rails”) is one approach (3).

However, the treatment couch typically has to be moved/rotated in between CT imaging and treatment. CT-on-rails can, thus, be considered a quasi-on-board verification system.

Cone beam CT (CBCT) images can be generated by rotating the gantry (along with mounted on-board kV imagers) about the patient. CBCT permits 3D imaging of the patient on the treatment machine and in the treatment position. CBCT prior to the delivery of radiation can assure placement of the target relative to the treatment isocenter (14, 15). We have developed and successfully implemented cone-beam CT into the treatment of our patients receiving conformal hypofractionated/radiosurgery for tumors in a variety of sites. This paper reports our technique and preliminary results.

**Materials and Methods**

**Description of the Clinical Procedures**

The protocol is illustrated in Figure 1. CBCT was used for image guidance. If patient motion was observed through the video camera monitoring system, the patient would be repositioned and new CBCT images were then acquired. Soft tissue was used for image guidance in lung and liver SBRT treatments. Images acquired before and after treatment were used to determine intrafraction motion.

**Immobilization and Simulation**

Patients selected for SBRT were immobilized with a customized alpha cradle. Patients with tumors in the thoracic and upper abdominal region were simulated using 4-D CT (GE light speed, GE, Milwaukee) to evaluate respiratory excursion. A respiratory gating device (RPM, Varian Medical Systems, Palo Alto, CA) monitored the breathing pattern. CT data with free-breathing, breath-hold, and phase-gated 4D CT were acquired. All three sets of CT images were reviewed by the treating radiation oncologist to select which CT set should be used for treatment planning. This was based on extent of respiratory motion, patient’s compliance, tumor location, and the adjacent normal structures. After the CT set was selected, these images were imported to the Eclipse treatment planning system (Varian medical Systems, Palo Alto, CA).

**Treatment Planning**

Treatment planning was performed using the Eclipse planning system. Images were segmented by the physician to define the GTV, and margin applied to define the CTV and PTV. The CTV ranged 2 ~ 153 c.c. in volume. If treatment was delivered using free breathing, an ITV was defined as well. When clinically indicated, MR and/or PET images were fused with the treatment planning CT using manual registration methods. Treatment techniques included dynamic conformal arcs, multiple conformal beams, or multiple intensity-modulated beams.

**Pre-treatment Target Localization**

Initial 2-D orthogonal radiographic images were taken to assess position. CBCT images were acquired and matched to the planning CT by the physician based on 3D anatomic information. Registration software on the radiation treatment unit...
was used to compare the CBCT and planning CT and to apply isocenter shifts per physician’s judgment. Vertebal bodies were used for the image guidance of spinal treatments and soft tissues were used for lung and liver treatments. 3D images were used for treatment guidance for all cases. The 2D images were used for monitoring the patient position during treatments. The organ motion was managed with RPM gating system. Three fiducial markers were implanted for the liver case. After shifting the patient, another set of 2-D kv/MV radiographs (or 3-D CBCT) was acquired as confirmation.

Treatment and Post-treatment Imaging

After the physician approved the patient localization, treatment was delivered by a Varian 21EX machine with 120-leaf millennium MLC (Varian Medical Systems, Palo Alto, CA). This machine is equipped with an on-board imager (OBI) and electronic portal imager, which are orthogonally mounted on the treatment gantry. After treatment was delivered, a pair of 2-D images or CBCT were acquired. These were compared to the pre-RT (post-CBCT) orthogonal images to assess for intra-fraction motion. This procedure was repeated prior to each treatment. By comparing the initial pre-RT 2D planar kv/MV images to the 3D CBCT images, the residual soft tissue error (as described above) was scored. By comparing the pre- and post-treatment images, the extent of intra-fraction motion was assessed.

Results and Discussion

Pre-RT CBCT images were evaluated for a total of 29 treatments in 10 patients undergoing stereotactic body radiosurgery according to an IRB approved protocol. The treatment sites included lung, liver, spine, adrenal gland, and rib. The difference between the isocenter shift obtained from the initial 2D orthogonal kv radiograph and CBCT is shown in Figure 2(a). The mean and standard deviation of the magnitude of the shifts were 0.34 ± 0.31 cm, 0.26 ± 0.33 cm, 0.14 ± 0.16 cm in the anterior-posterior, left-right, and superior-inferior directions, respectively.

The degree of intra-fractional motion detected by the comparison of the pre-RT and post-RT images was shown in Figure 2(b). The mean and standard deviation of the magnitude of the shifts were 0.092 ± 0.096 cm, 0.094 ± 0.071 cm, 0.12 ± 0.10 cm in the anterior-posterior, left-right, and superior-inferior directions, respectively.

The 2D matching was based on bony landmarks such as vertebral bodies. The 3D matching was based on target volumes. Internal organ motion, rotational setup errors, and other factors may contribute to the differences between 2D and 3D images. After patients were re-positioned after 3D matching, another set of 2D images was taken as the pre RT baseline position. There was no repositioning between the pre- and post- RT imaging.

Case Illustrations

Paraspinal metastasis (rigid body): Patient #1 had a recurrent paraspinal metastasis from lung cancer despite previous palliative RT (3Gy x 13 fractions). The patient was immobilized in an alpha-craddle and a CT simulation was performed. The extent of tumor extension into the vertebral body was assessed via the CT and PET. A 12 cc GTV was identified. No expansion was used for the CTV. A 5-mm margin was added for the PTV (37.3 cc). The prescription dose was 10 Gy x 3 fractions to the 95% isodose line (normalized to the isocenter). The radiation plan used six co-planar IMRT fields with mixed energies of 6 MV and 15 MV. After the patient was positioned on the table, 2D kv orthogonal images were taken and compared to reference DRRs. The patient was repositioned based on the 2D kv orthogonal images. Next, a CBCT was acquired and 3D matching between the CBCT and the planning CT using soft tissue and bone anatomy was performed. The patient was then repositioned again based on the CBCT matching results and additional 2D orthogonal images taken for documentation. After treatment, an additional set of images documented the treatment accuracy. Figure 3(a) shows the 3D planning CT and Figures 3(b) and 3(c) show the 3D CBCT matching with the planning CT. The CBCT shifts were 2 mm, 0 mm, and 4 mm in the anterior-posterior, left-right, and superior-inferior directions, respectively. The 2D radiographs before and after treatment (Figure 3d). The intra-fractional shifts were 0 mm, 2 mm, and 1 mm in the anterior-posterior, left-right, and superior-inferior directions, respectively. Follow-up PET/CT images (Figure 3e) showed an excellent response to treatment.

Liver (breath hold): Patient #2 had metastatic breast cancer with symptomatic liver metastases. This patient was treated under breath-hold with amplitude gating to minimize the effect of organ motion. A planning CT scan was acquired with the patient in breath hold. The depth of the breath hold was monitored with a Varian RPM respiratory gating system. Clips were placed into the liver to assist with localization. A GTV was contoured on the breath-hold CT with a volume of 153.3 cc. The GTV was then expanded by 5 mm in 3D space to yield a PTV. A 5-field IMRT plan was created with 6X/15X mixed energies to deliver 30 Gy to PTV in 5 fractions. In the treatment room, the patient was initially set up with orthogonal kv radiographs and then CBCT was acquired for final localization. Figure 4 shows the CBCT image matched to the planning CT image. The shifts based on the CBCT matching were 9 mm, 5 mm, and 6 mm in the anterior-posterior, left-right, and superior-inferior directions, respectively. Figure 5 shows the 2D kv radiographs during the initial setup before 3D-3D matching (a), after 3D-3D...
matching and before treatment (b), and after the treatment was completed (c). The clips can be seen in the radiographs around 1-2 cm superior to the isocenter. The shifts between the pre- and post-treatment images were 0.5 mm, 2.5 mm, and 3 mm in the anterior-posterior, left-right, and superior-inferior directions, respectively. This indicated that the patient position was well maintained during the treatment. Figure 6 shows the PET images before treatment (left) and 1 month after treatment (right). PET hypermetabolic activity decreased markedly after the treatment.

Figure 3: Spine case: 3-D planning (a), 3-D CBCT matching with planning CT [(b)-before matching, and (c)-after matching], 2-D radiograph before and after treatment (d), and treatment outcome of PET images (e).

Figure 4: CBCT for the liver case after matching with planning CT (shown with contours).
Figure 5: kV radiographs for the liver case taken (a) before correction, (b) after correction but before treatment, (c) after treatment. Implanted markers are used to document the deviations.

Figure 6: Treatment outcome as shown in PET images: pre-treatment PET (left) and 1 month after the treatment (right).

Figure 7: (a) Plan; (b) CBCT pre-shift; (c) CBCT after shift before treatment; and (d) CBCT after treatment.
Lung (free breathing):  Patient #3 had metastatic breast cancer with a solitary lung metastasis. A 4D CT scan was acquired to determine an ITV. The volume of the ITV was 1.9 cc. The ITV was expanded to make a PTV by using 3D margins of 10 mm along the superior-inferior direction and 5 mm in all other directions. Four dynamic arcs were used to deliver 30 Gy in 2 fractions to the PTV. The plan is shown in Figure 7(a). The CBCT was acquired for treatment localization and shown in Figure 7(b). The CBCT images were matched to the ITV as shown in Figure 7(c). The couch was shifted 5 mm, 1 mm, and 2 mm in the anterior-posterior, left-right, and superior-inferior directions, respectively, based on the CBCT matching. Another CBCT was acquired after the treatment was completed and shown in Figure 7(d). The shifts between the pre-treatment and post-treatment CBCT images were 4 mm, 2 mm, and 2 mm in the anterior-posterior, left-right, and superior-inferior directions, respectively.

Discussion

This study illustrates several points. First, CBCT is clinically feasible to implement in the treatment of patients undergoing stereotactic body radiotherapy. The degree of difference between the isocenter set-up via 2D planar images and the CBCT is on average 5 mm. The clinical significance of this is debatable and depends on the clinical site, situation, et cetera.

Second, the degree of intra-fractional motion is small, and thus there is little need to image the target during treatment. In this prospective study, kV orthogonal radiographs or CBCT images were acquired post-radiation treatment to verify accuracy of patient setup after the treatment delivery. If the patient moved from the setup position, the post treatment kV radiographs or CBCT images would effect this change. Although alpha-craddles were used for immobilization, the shift between the pre- and post-treatment images was within 2 mm in the majority of treatments; occasionally the shift was as high as 4 mm. The shifts during the treatment were within the margins used in the treatment planning. Carefully made alpha-craddles can be used as a treatment immobilization device for body radiosurgery if patient is judged to be stable. The treatment accuracy may be further enhanced by improving immobilization devices.

The CBCT shifts were measured by manually matching the 3D CBCT images to the reference planning CT images. The 2D radiograph shifts were measured by match kV radiographs to the DRR images. There are many factors that contribute to the measurement uncertainty, such as the resolution of the kV detector and the isocenter accuracy. The overall uncertainty is approximately 1 mm.

With on-board CBCT images, treatment localization is based on 3D patient anatomy. Both bony structures and soft tissues can be used to match planning CT images. After adjusting display window and level properly, tumor target may also be identified on CBCT images. The improvement of localization accuracy by using CBCT over orthogonal 2D images may up to 1.5 cm (as shown in Figure 2b). This result is based on 2D kV radiographs. If 2D MV images are used, the improvement realized by using CBCT for localization may be more significant since the image quality of MV images is not as good as kV images.

CBCT guided SBRT requires rigorous quality assurance program to verify that the CBCT isocenter is the same as the MV isocenter. Other challenges include improving soft tissue contrast of CBCT images and internal organ motion management. The reproducibility of isocenter localization is within a millimeter with CBCT QA phantoms.

Conclusion

A CBCT-based SBRT technique is proposed. The technique allows physicians to set up the treatments based on 3D anatomical information prior to treatment, permitting highly accurate treatment delivery.

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References


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