Published in final edited form as:

Phys Med Biol. 2012 February 07; 57(3): 757–769. doi:10.1088/0031-9155/57/3/757.

An End-to-End Examination of Geometric Accuracy of IGRT Using a New Digital Accelerator Equipped with On-Board Imaging System

Lei Wang, Kayla N. Kielar, Ed Mok, Annie Hsu, Sonja Dieterich, and Lei Xing

Department of Radiation Oncology, Stanford University School of Medicine, Stanford, CA

Abstract

The Varian's new digital linear accelerator (LINAC), TrueBeam™ STx, is equipped with high dose rate flattening filter free (FFF) mode (6 MV and 10 MV), high definition multileaf collimator (HDMLC) (2.5 mm leaf width), as well as onboard imaging (OBI) capabilities. A series of end-to-end phantom tests were performed TrueBeam-based IGRT to determine the geometric accuracy of image-guided setup and dose delivery process for all beam modalities delivered using IMRT and RapidArc™. In these tests, an anthropomorphic phantom with a Ball Cube II insert and the analysis software (FilmQA™ (3cognition)) were used to evaluate the accuracy of TrueBeam™ image-guided setup and dose delivery. Laser cut EBT2 films with 0.15 mm accuracy were embedded into the phantom. The phantom with the film inserted was first scanned with a GE Discovery-ST CT scanner, and the images were then imported to the planning system. Plans with steep dose fall off surrounding hypothetical targets of different sizes were created using RapidArc and IMRT with FFF and WFF (with flattening filter) beams. Four RapidArc plans (6 MV and 10 MV FFF) and five IMRT plans (6 MV and 10 MV FFF; 6 MV, 10 MV and 15 MV WFF) were studied. The RapidArc plans with 6 MV FFF were planned with target diameters of 1 cm (0.52 cc), 2 cm (4.2 cc), and 3 cm (14.1 cc), and all other plans were planned with a target diameter of 3 cm. Both onboard planar and volumetric imaging procedures were used for phantom setup and target localization. The IMRT and RapidArc plans were then delivered, and the film measurements were compared with the original treatment plans using a Gamma criteria of 3%/1 mm and 3%/2 mm. The shifts required in order to align the film measured dose with the calculated dose distributions was attributed to be the targeting error. Targeting accuracy of image-guided treatment using TrueBeam™ was found to be within 1 mm. For irradiation of the 3 cm target, the Gammas (3%, 1 mm) were found to be above 90% in all plan deliveries. For irradiations of smaller targets (2 cm and 1 cm), similar accuracy was achieved for 6 MV and 10 MV beams. Slightly degraded accuracy was observed for irradiations with higher energy beam (15 MV). In general, Gammas (3%, 2 mm) were found to be above 97% for all the plans. Our end-to-end tests showed an excellent relative dosimetric agreement and sub millimeter targeting accuracy for 6 and 10 MV beams, using both FFF and WFF delivery methods. However, increased deviations in spatial and dosimetric accuracy were found when treating lesions smaller than 2 cm or with 15 MV beam.

Keywords

IGRT; image guided delivery; Flattening Filter Free field; film dosimetry; end-to-end test

1. Introduction

The past decade has witnessed a steady improvement in dose delivery technique and image guidance strategy and image guided radiation therapy (IGRT) has become part of routine clinical practice in many clinics around the world (Timmerman and Xing, 2009). One of the most important issues in IGRT is how to ensure the performance of each step in the increasingly sophisticated radiation therapy workflow so that a planned dose distribution can be realized with high fidelity in a clinical setting. The issue becomes even more critical with the increased demand for highly conformable dose distributions in latest clinical protocols with hypo-fractionated dose prescriptions. While the ultimate success of an IGRT program depends on multiple factors such as mechanical accuracy and stability of the dose delivery system, performance of the image guidance tools (Boda-Heggemann et al. 2011; Korreman et al. 2010; Xing et al. 2006), integration of various steps involved in the treatment, training of staff, and effectiveness of quality assurance (QA) procedure, a systematic examination or an end-to-end test of the treatment planning and dose delivery system is a prerequisite to the overall success of any IGRT program.

In meeting with the increased clinical demands for higher mechanical accuracy, improved intra-treatment image guidance, and faster dose delivery, a new generation of digital LINAC, such as the Varian TrueBeam™ system, has become commercially available. Hrbacek et al (Hrbacek et al. 2011) have recently reported their experience in commissioning the system for clinical use. One of the first three TrueBeam™ STx LINACs from Varian Medical Systems was installed at Stanford University Hospital and commissioned for clinical use in 2010. The system is equipped with Flattening Filter Free (FFF) mode (6 MV and 10 MV) (Cho et al. 2011; Georg et al. ; Hrbacek et al. 2011 ; Kim et al. 2011; Kragl et al. ; Kry et al. 2009), a High Definition Multileaf Collimator (HDMLC) (2.5 mm leaf width), as well as On-Board Imaging (OBI) and Cone Beam CT (CBCT) capabilities, and provides an excellent platform for IGRT application. In the process of clinically implementing the novel TrueBeam™ STx based IGRT program, a series of end-to-end test of the system was designed and carried out to determine the accuracy of beam targeting and dose delivery achievable by the system. This was performed after complete commissioning of the LINAC and Eclipse treatment planning system, which included thorough and rigorous testing of the novel FFF mode combined with an HDMLC. These end-to-end tests provide us with a comprehensive appreciation of the overall performance of the system. In this paper, we report our experimental design and experience gained during this study.

2. Materials and Methods

2.1. Head Phantom and Ball Cube

A head phantom (Figure 1) with a Ball Cube insert (Figure 2) has historically been used for end-to-end QA of CyberKnife QA (Chang et al. 2003; Yu et al. 2004)(Cyberknife Physics Essential, Accuray Inc. 2009). The Ball Cube is a 2.5 inch acrylic cubic with a 3 cm diameter circular target in the center. The Ball Cube holds two orthogonal (axial and sagittal) films, and has four notches at each axial and sagittal plan, tightly holding the pre-cut Gafchromic films in the cube. The CT coordinates of the eight notches are used to register the film during analysis. Specific laser cut Gafchromic films (Hayes Inc., Santa

Clara, CA) with 0.15 mm cutting accuracy were used in this study. The laser cut pattern is used to determine the film orientation, and the four laser cut holes on each film are used to accurately place the film into the four notches within the Ball Cube II.

The CyberKnife end-to-end test is usually created using one circular cone and optimized to deliver a dose distribution centered to the spherical target inside the cube. A specific end-to-end test software developed by Accuray analyzes the film and compares the center of the measured dose distribution on the film with the center of the target determined from the film size. The agreement between the two is defined as the targeting accuracy, and studies have shown that the overall accuracy of this technique is estimated to be ± 0.3 mm (Cyberknife Physics Essential, Accuray Inc. 2009). The CyberKnife end-to-end test verifies the entire treatment process from CT simulation to the end of image guided delivery with sub millimeter accuracy. This is advantageous over other QA methods which test each parameter individually. One of the disadvantages of this method is that it does not provide dosimetric information. It also requires that the planned dose be perfectly aligned and symmetric to the center of the target, and is therefore not adequate for the purpose of patient QA. However, when combined with automatic dose registration provided in FilmQATM (3cognition) software, dosimetric accuracy using film can be performed, and thus overcomes this shortage of the CyberKnife end-to-end test (Hsu et al. 2010).

2.2. Film Dosimetry

A set of laser cut films used to provide dosimetric and targeting accuracy in this study are shown in Figure 3. Figure 3(A) is the calibration film which is cut into eight pieces, providing a calibration dose curve. Figure 3(B) and Figure 3(C) are the sagittal and axial pre-cut Gafchromic EBT2 films (Hayes Inc., Santa Clara, CA), respectively. Sagittal films are denoted Anterior-Superior (AS) and axial films are denoted Anterior-Left (AL) based on patient direction. Use of Gafchromic films in IMRT QA has been increasing in the past several years due to their near-tissue equivalence, radiation beam energy independence, high spatial resolution, and self-developing properties (Niroomand-Rad et al. 1998; Wilcox and Daskalov 2007). Compared to EDR2 films that are also regularly used in IMRT QA, EBT2 films have less sensitivity, and can be exposed to higher doses (up to 8 Gy for the red channel). Thus, these are the better choice for performing IGRT QA. Gafchromic MD 55 films have an even larger dynamic range (up to 30 Gy), which would be ideal, however, pre-cut films are not available from the manufacturer and targeting accuracy cannot be reliably tested. Gafchromic films such as EBT2 do have a few disadvantages: their response changes with time, especially for the first 24 hours after irradiation; they have varying responses depending on the wavelength of scanning light as well as scanning direction. The response of the films may also vary between different batches and among sheets. With careful and correct procedures, EBT/EBT2 films can be used as absolute dosimeter with around 3% accuracy. In this case, absolute point dose verification is routinely implemented during patient QA, so it is of less concern in this study. Instead, focus was put on absolute targeting accuracy and relative dose agreement for reliability.

2.3. Simulation

The head phantom with the Ball Cube II loaded with previously irradiated films was first scanned using a GE Discovery ST scanner (General Electric Co.) at 1.25 mm slice thickness. The CT images were then imported into the Eclipse treatment planning system (version 8.9). The purpose of previously irradiated films loaded into the Ball Cube during the CT scan was to eliminate the localization inaccuracy introduced by the film thickness. A total of nine plans were created with different energies and delivery modalities. Plans were also created either With Flattening Filter (WFF) or Flattening Filter Free (FFF). Five IMRT plans (6 MV and 10 MV FFF; 6 MV, 10 MV and 15 MV WFF) and two RapidArc plans (6 MV and 10 MV FFF) were created with target diameter of 3 cm (14.1 cc). To investigate the TrueBeam™ systems limit on smaller target sizes, two RapidArc plans were created using 6 MV FFF to target a lesion with diameters of either 2 cm (4.2 cc) or 1 cm (0.52 cc). All of the plans were optimized to have a steep dose fall off surrounding the target, and with a dose calculation grid of 1 mm. RapidArc plans were planned with two full arcs with 45 and 315 degree oblique collimator angles that are typical in clinical treatment planning. All the IMRT plans were planned with 7 equally spaced non parallel apposed coplanar beams. All plans were optimized with the criteria of 90% isodose line covering more than 95% of the target volume, and normalized to deliver 600 cGy to the dose maximum. This prescription dose was chosen due to the fact that the EBT2 film has a dynamic range of up to about 800 cGy for the red channel signal.

2.4. Plan delivery and verification

Plans were delivered on the TrueBeam™ using both planar imaging and CBCT as the guidance in locating the isocenter. Simulating an actual patient treatment, the phantom was first set up with the help of the lasers on the wall. Then, a pair of kV images was taken, and 2D-2D auto matching procedure was applied with the matching window set to enclose most of the skull as shown in Figure 4(A). After applying the suggested table shift determined by the kV image pairs, a CBCT and 3D-3D auto matching procedure was performed as shown in Figure 4(B). The position determined from CBCT was used for final delivery for all the plans in this study. Calibration films were exposed at eight doses (0 cGy, 100 cGy, 200 cGy, 300 cGy, 400 cGy, 500 cGy, 600 cGy and 700 cGy) for all energies directly after the experimental delivery. The machine was calibrated to deliver 1 cGy per Monitor Unit (MU) with 10 cm square field size at the depth of dose maximum at 100 cm SSD. The FFF mode was calibrated independently in the same way as WFF mode.

2.5. Film processing and data analysis

Since film response changes with time, especially during the first 24 hours after irradiation, films were held one day for self-development(Niroomand-Rad et al. 1998). EBT2 films were then scanned with an Epson scanner (Epson Expression 10000 XL) using 48-bit transmission mode through the red color channel at a resolution of 96 dpi, and saved in tagged image file format (TIFF). Following FilmQA software manufacturer recommendations, no color correction was applied during the scanning process. Since the response of EBT2 films has a strong dependence on scanning orientation, the scanning direction was carefully controlled for all calibration and measurement films. Films were

scanned with the smooth side facing up and the laser cut slid pointing in the vertical direction. To reduce the response from variance inherent in the scanner, films were placed at identical locations in the center of the scanner. Because of the small size of the film, non-uniformity introduced from the scanner was ignored. No background subtraction process was applied.

Scanned films were analyzed using FilmQA™ (3cognition LLC) software. In order to use the auto registration procedure specially developed for the Ball Cube II, the same CT set was first exported to the CyberKnife Multi Plan system. The eight notches that fit into the laser cuts on the films were identified as alignment fiducial markers for tracking. A simple plan (isocentric) was created, and its xml file (a file with tracking and path information) was saved to a disk. Using the information from the xml file (CT coordinates of the notches), FilmQA was able to automatically register the film with the calculated doses exported from the Eclipse planning system. According to the manufacturer, the accuracy of the laser cut is within 0.15 mm, therefore this procedural system is capable of registering the measured films to the calculated dose distribution with an accuracy comparable to 0.15 mm.

The measured dose using film was compared with the calculated dose using Eclipse, and analyzed using a Gamma criterion (Low and Dempsey 2003) of 3%/1 mm and 3%/2 mm. The Gamma criterion is widely used in IMRT QA to assess dose agreement between measured and calculated dose, and evaluates the dose difference as well as the distance to agreement (DTA). During this study, Gamma was calculated in a square region of interest just large enough to cover the high dose region and was normalized to the center of the field. Targeting accuracy was measured using a manual shift method. The shift required to align the film with the calculated dose after auto-registration was estimated to be the targeting error. Given the steep dose fall off in typical small target radio-surgery treatment plans, a manual shift ensures any targeting error is easily and accurately removed.

2.6. Reproducibility and Accuracy of experimental study

Stability and accuracy of the image guidance system are essential in treatment delivery. The following checks were performed to assess the accuracy and experimental reproducibility of the study.

2.6.1. 2D and CBCT image guidance consistency—With an arbitrary initial position, the table was first moved to the position suggested by the 2D-2D matching process as described in the previous section. To eliminate the error introduced in table shifting, a verification kV imaging pair was taken and the recommended residue table shift was recorded without shifting the table. A CBCT and 3D-3D auto matching process was then performed. The recommended table shift was recorded and compared with the table shift recommended by the 2D verification imaging measurements. This procedure was repeated 7 times with different starting positions.

2.6.2. Evaluation of the accuracies of 2D and 3D image guided phantom setup procedures—The accuracies of phantom setup procedure based on kV image pair and volumetric CBCT were assessed independently for the TrueBeam™ system. The phantom was first moved to the treatment delivery position (iso-center) under the guidance of onboard

kV image pair using the standard 2D-2D matching. Seven randomly chosen shifts of the couch were then introduced with respect to the isocenter, with the movement amplitude ranging from 1 mm to 2.5 cm (The Varian Exact IGRT couch position accuracy was better than 0.1 mm as determined during acceptance tests of the TrueBeam™). The 2D-2D image guided patient setup procedure was applied again to bring the phantom back to its original positions. The agreement between the movement suggested by the 2D-2D matching and the known couch shift was computed and employed as a metric for evaluating the accuracy of the 2D-2D matching. The same tests were applied to examine the CBCT-based phantom setup procedure.

2.6.3. Reproducibility in targeting error measurement—The above tests examine the consistency and accuracy of the image guidance system. To test the reproducibility of the dose delivery and film measurements, the same Rapid Arc plan with 6 MV FFF and 3 cm target size was delivered three times, and the films were then analyzed. Before each of the three deliveries, a CBCT scan was done and auto matching was performed and the suggested table position was used for the final delivery for the corresponding delivery. The initial starting position of the phantom was chosen randomly.

3. Results

The image guidance resulted from planar OBI 2D-2D auto-matching and volumetric CBCT auto-matching agreed each other consistently. The average difference in measured positioning using kV 2D-2D matching and CBCT alignment was $0.1 \text{ mm} \pm 0.2 \text{ mm}$ in each orthogonal direction and was $0.4 \text{ mm} \pm 0.1 \text{ mm}$ in total absolute distance. Thus, once the OBI was used to align the phantom with the isocenter during the initial setup, the CBCT for verification did not require a shift of more than 0.5 mm for any of the treatment deliveries performed in this study.

With the accuracy tests described in Sec. 2.6.2, we found that the CBCT procedure was slightly more accurate than 2D-2D matching procedure, and was much more robust when shifts more than 1 cm were introduced. The accuracy of the 2D-2D auto-matching procedure was found to be $0.2 \pm 0.1 \text{ mm}$ in each orthogonal direction when the intentionally introduced shift was within 1 cm. When the shift exceeded 1 cm, it was found that the 2D-2D matching results were less satisfactory and may fail to provide acceptable solutions, primarily due to the image distortion arising from the magnification and beam divergence. The CBCT auto-matching was found to be consistently accurate to within 0.15 ± 0.1 in each orthogonal direction, even when the couch shifts were as large as 2.5 cm.

Overall, excellent relative dose agreement between measured and calculated dose for all of the measurements was found. Shown in Figures 5 and 6 are the measured versus calculated doses in the axial plane for 6 MV FFF and 10 MV FFF arc plans, respectively. In these two figures, X corresponds to patient right-to-left (RL) direction, and Y corresponds to patient anterior-to-posterior (AP) direction. The doses were normalized to the origin. In the profiles, green and purple denote the calculated and measured data, respectively. In the isodose comparison, thicker lines are the calculated doses. As shown, the measured and calculated

isodose lines nearly superimpose. Gamma (3%, 1mm) results are displayed in the right lower corner, and are greater than 99% for both cases.

The targeting error is highlighted in Figure 7 by overlaying the isodose comparison before and after removing the applied manual shift for the 6 MV FFF arc plan in the sagittal plane. Figure 7(A) shows the isodose comparison of the anterior-superior (AS) film before the manual shift was applied. In the AS film (sagittal plane), X corresponds to the patient superior-to-inferior (SI) direction, and Y corresponds to patient anterior-to-posterior (AP) direction. The slight disagreement between the measured isodose line (thinner line) and the calculated isodose line (thicker line) is visible in the SI direction. After the targeting error is removed, as shown in Figure 7(B), the isodose lines nearly superimpose each other. In this case the measured shift is -0.4 mm in the X direction (SI) and 0.1 mm in Y direction (AP).

Overall results in the targeting accuracy for the nine plans are summarized in Table 1. Targeting accuracy was found to be within 1 mm in all three orthogonal directions. Anterior-to-posterior targeting error was measured for both orthogonal films and the results were averaged. It was noticed that errors from the two films were self-consistent within 0.3 mm. Total error was calculated and is given in the last column. Slightly larger targeting error was found in superior-inferior direction for all the plans, and could be due to geometric limits from the MLC leaf width.

The reproducibility data of the measurements for the delivery of Rapid Arc plan with 6MV FFF and 3 cm target are shown in Table 2. It was found that the three measurements agreed to within 0.2 mm.

The Gamma (3%, 1mm) for all the plans was found to be above 90% except for plans with smaller target sizes (2 cm and 1 cm) and higher energy (15 MV). However, with a less stringent DTA, the Gamma (3%, 2 mm) all the plans were found to be above 97%. The results were shown in Table 3.

4. Discussion

An end-to-end test of the Varian TrueBeam™ STx system has been performed to assess the dosimetric and targeting accuracy for small lesions. Using the head phantom with the Ball Cube II and FilmQA software is a useful procedure for verifying the image-guided setup and dose delivery of the system. Targeting accuracy using image guided delivery was found to be within 1 mm for all nine plans studied. The relative dose agreement also proved to be accurate. This method verifies the entire treatment procedure from simulation to delivery and is a comprehensive validation of CT simulation, treatment planning and dose calculation, image guidance and machine delivery. This method can be a valuable tool for LINAC commissioning, monthly and annual QA, as well as patient specific QA.

During treatment delivery, it was found that image guidance using planar OBI 2D-2D auto-match and a 3D CBCT auto-match agreed within 0.5 mm. Thus, the image-guided delivery of the system is quite consistent for a rigid object. Couch auto shifting from outside the room was only available in three translational directions, thus rotations from initial laser setup were adjusted manually. Had a 6D couch been available, patient straightness and

rotations would be aligned automatically. However, this is not implemented clinically, and since the target is spherical, the effect on setup error due to rotation is minimal.

The total targeting accuracy with image-guided delivery was found to be within 1 mm in all three orthogonal directions. All nine plans were based on one CT phantom scan at 1.25 mm slice thickness. A high resolution dose grid (1 mm) was also used in dose calculation. A lower resolution in dose calculation and a smaller slice thickness could potentially introduce more dosimetric error¹³. Slightly higher targeting error was found in the superior-to-inferior direction, ranging from −0.4 mm to −0.8 mm. This could be due to the lower resolution of CT images in this direction. It also could be a limitation based on geometry and the MLC leaf width¹³. All plans were based on the same CT scan, which explains the targeting error consistency with direction. Overall, this systematic targeting inaccuracy is not significant when compared with the other two directions.

The method reproducibility test demonstrated the robustness of the image guidance and the accuracy of the measurement method. The deliveries were performed at the same night to reduce the systematic error caused by the imaging guidance.

Due to the limitation on film dose accuracy, absolute dosimetry was not used in this study for comparison. It is noted, however, that excellent relative dose agreement was achieved. An increased deviation in spatial and dosimetric accuracy was found for 15 MV measurements and lesions less than 2 mm (Table 3). For higher energies and smaller field sizes, the electron lateral disequilibrium effect is more pronounced, and this may explain the slightly increased inaccuracy of these three plans. Further investigation is required to validate the capability of this system for targets smaller than 2 cm.

An end-to-end test similar to the one used in this study could also be used for patient specific QA. However, the films are expensive, and may be too time consuming for routine clinical work. Future studies will include applying this method to other treatment sites, such as pelvic and thorax anatomy. With motion platforms, this system will lend itself well to being a valuable tool in assessing the targeting and dosimetric accuracy for gated treatment delivery.

5. Conclusion

An end-to-end test using a head phantom with Ball Cube II insert and FilmQA analyzing software has been performed to determine the targeting and dosimetric accuracy of the overall delivery for the TrueBeam™ STx system. Excellent relative dosimetric agreement and sub millimeter targeting accuracy were achieved for 6 MV and 10 MV beams both WFF and FFF and for static IMRT and RapidArc delivery. For smaller lesions or higher energy (15MV), a slight degradation in the achievable accuracy is observed and improved dosimetric model may be useful to improve the situation.

Acknowledgments

We would like to thank Varian Medical Systems for their funding and technical support. We would also like to acknowledge funding from the NIH (1R01 CA104205 and 1R21 CA153587). We are also grateful to Drs. Michelle Svatos, Peter Munro, Josh Star-Lack, and Mark Wanlass for their useful discussions.

References

- Boda-Heggemann J, Lohr F, Wenz F, Flentje M, Guckenberger M. kV Cone-Beam CT-Based IGRT : A Clinical Review. *Strahlenther Onkol.* 2011; 187(5):284–291. [PubMed: 21533757]
- Chang SD, Main W, Martin DP, Gibbs IC, Heilbrun MP. An analysis of the accuracy of the CyberKnife: a robotic frameless stereotactic radiosurgical system. *Neurosurgery.* 2003; 52(1):140–146. discussion 146–147. [PubMed: 12493111]
- Cho W, Kielar KN, Mok E, Xing L. Multisource modeling of flattening filter free (FFF) beam and the optimization of model parameters. *Med Phys.* 2011; 38(4):1931–1942. [PubMed: 21626926]
- Georg D, Knoos T, McClean B. Current status and future perspective of flattening filter free photon beams. *Med Phys.* 38(3):1280–1293.
- Hrbacek J, Lang S, Klock S. Commissioning of photon beams of a flattening filter-free linear accelerator and the accuracy of beam modeling using an anisotropic analytical algorithm. *Int J Radiat Oncol Biol Phys.* 2011; 80(4):1228–1237. [PubMed: 21129855]
- Hsu, A.; Wang, L.; Dieterich, S. Patient Specific Delivery Quality Assurance for Robotic Stereotactic Radiosurgery of Functional Targets. In: Hendee, WR., editor. *Med Phys; AAPM Annual Meeting; Philadelphia, Pennsylvania.* 2010. p. 3308
- Kim T, Zhu L, Suh T, Geneser S, Xing L, Meng B. Inverse planning for IMRT with nonuniform beam profiles using total-variation regularization (TVR). *Med Phys.* 2011; 38(1):57–66. [PubMed: 21361175]
- Korremans S, Rasch C, McNair H, Verellen D, Oelfke U, Maingon P, Mijnheer B, Khoo V. The European Society of Therapeutic Radiology and Oncology-European Institute of Radiotherapy (ESTRO-EIR) report on 3D CT-based in-room image guidance systems: a practical and technical review and guide. *Radiother Oncol.* 2010; 94(2):129–144. [PubMed: 20153908]
- Kragl G, af Wetterstedt S, Knausl B, Lind M, McCavana P, Knoos T, McClean B, Georg D. Dosimetric characteristics of 6 and 10MV unflattened photon beams. *Radiother Oncol.* 2009; 93(1):141–146. [PubMed: 19592123]
- Kry SF, Howell RM, Polf J, Mohan R, Vassiliev ON. Treatment vault shielding for a flattening filter-free medical linear accelerator. *Phys Med Biol.* 2009; 54(5):1265–1273. [PubMed: 19190359]
- Low DA, Dempsey JF. Evaluation of the gamma dose distribution comparison method. *Med Phys.* 2003; 30(9):2455–2464. [PubMed: 14528967]
- Niroomand-Rad A, Blackwell CR, Coursey BM, Gall KP, Galvin JM, McLaughlin WL, Meigooni AS, Nath R, Rodgers JE, Soares CG. Radiochromic film dosimetry: recommendations of AAPM Radiation Therapy Committee Task Group 55. *American Association of Physicists in Medicine. Med Phys.* 1998; 25(11):2093–2115. [PubMed: 9829234]
- Timmerman, R.; Xing, L., editors. *Image Guided and Adaptive Radiation Therapy.* Lippincott, Williams, and Wilkins; Baltimore, MD: 2009.
- Wilcox EE, Daskalov GM. Evaluation of GAFCHROMIC EBT film for Cyberknife dosimetry. *Med Phys.* 2007; 34(6):1967–1974. [PubMed: 17654899]
- Xing L, Thorndyke B, Schreiber E, Yang Y, Li TF, Kim GY, Luxton G, Koong A. Overview of image-guided radiation therapy. *Med Dosim.* 2006; 31(2):91–112. [PubMed: 16690451]
- Yu C, Main W, Taylor D, Kuduvali G, Apuzzo ML, Adler JR Jr. An anthropomorphic phantom study of the accuracy of Cyberknife spinal radiosurgery. *Neurosurgery.* 2004; 55(5):1138–1149. [PubMed: 15509320]

Figure 1.
The head phantom with the Ball Cube II inserted.

Figure 2.
The Ball Cube II with the pre-cut EBT films.

Figure 3.
Exposed EBT2 films. A) Calibration films, which are cut from one pre-cut EBT2 film. B) Sagittal film or Anterior-Superior film (AS). C) Axial film or Anterior-Left film (AL).

Figure 4.

(A) An example of 2D-2D auto-matching window. (B) An example of CBCT auto-matching window. As with an actual treatment, we used 2D-2D match first, and confirmed with CBCT alignment. The OBI auto match function was used for all the measurements. The difference in measured positioning using kV 2D-2D matching and CBCT alignment was within 0.5 mm.

Figure 5.

Dose comparison for a 6 MV FFF RapidArc plan with 3 cm diameter target in the axial plane of the Anterior-Left (AL) film. X is the patient right-to-left direction, and Y is the patient anterior-to-posterior direction. In the profiles, green and purple denote the calculated and measured data, respectively. In the isodose comparison, thicker lines are the calculation. Gamma (3%, 1 mm) result is displayed in right lower corner.

Figure 6.

Dose comparison for a 10 MV FFF RapidArc plan with 3 cm diameter target in the axial plane for the Anterior-Left (AL) film. X is the patient right-to-left direction, and Y is the patient anterior-to-posterior direction. In the profiles, green and purple denote the calculated and measured data, respectively. In the isodose comparison, thicker lines are the calculation. Gamma (3%, 1 mm) result is displayed in right lower corner.

Figure 7.

6 MV FFF Arc plan targeting accuracy measurement. A) Isodose comparison of Anterior-Superior (AS) film before the manual shift was applied. B) Isodose comparison of AS film after the manual shift was applied. The measured shift in the X direction (SI) was -0.4 mm, and in the Y (AP) direction was 0.1 mm.

Table 1

Measured targeting accuracy for all nine plans. Anterior-to-posterior targeting accuracy was measured at both orthogonal films. The results were averaged, and total error magnitude was calculated in the last column.

Plan	AL film				AS film			
	Target Diameter (cm)	X(RL) (mm)	Y(AP) (mm)	X(SI) (mm)	Y(AP) (mm)	AP Average (mm)	Magnitude (mm)	
6MV FFF Rapid Arc	3	0	0	-0.4	0.1	0.05	0.40	
10MV FFF Rapid Arc	3	0	0	-0.7	-0.1	-0.05	0.70	
6MV FFF IMRT	3	0.5	-0.2	-0.5	-0.1	-0.15	0.72	
10MV FFF IMRT	3	0	0	-0.7	-0.1	-0.05	0.70	
6MV WFF IMRT	3	0.4	-0.2	-0.5	-0.2	-0.2	0.67	
10MV WFF IMRT	3	0.2	-0.3	-0.7	-0.4	-0.35	0.81	
15MV WFF IMRT	3	0.2	-0.2	-0.8	-0.1	-0.15	0.84	
6MV FFF Rapid Arc	2	-0.2	-0.5	-0.5	-0.2	-0.35	0.64	
6MV FFF Rapid Arc	1	0.3	-0.3	-0.4	-0.5	-0.4	0.64	

Results for reproducibility study. The Rapid Arc plan with 6MV FFF and 3 cm target size was used for this study. The results agreed well within 0.2 mm. They demonstrated the robustness of the image guidance and the accuracy of the measurement method.

Table 2

	AL film			AS film			Magnitude (mm)
	X (RL) (mm)	Y (AP) (mm)	X (AP) (mm)	X (SD) (mm)	Y (AP) (mm)	AP Average(mm)	
Delivery #1	0.2	-0.1	-0.7	-0.7	-0.2	-0.15	0.74
Delivery #2	0.2	-0.2	-0.8	-0.8	0	-0.1	0.83
Delivery #3	0.1	-0.3	-0.8	-0.8	0.1	-0.1	0.81
Average	0.17	-0.20	-0.77	-0.77	-0.03	-0.12	0.79

Table 3

Gamma index results for all nine plans. Dose was normalized to the origin using an ROI including the high dose region only.

Plan	AL film			AS film		
	Target Diameter (cm)	Gamma (3%, 1mm)	Gamma (3%, 2mm)	Gamma (3%, 1mm)	Gamma (3%, 2mm)	Gamma (3%, 2mm)
6MV FFF Rapid Arc	3	99.82%	100.00%	99.03%		99.30%
10MV FFF Rapid Arc	3	99.88%	100.00%	90.49%		99.35%
6MV FFF IMRT	3	92.90%	99.40%	90.56%		98.90%
10MV FFF IMRT	3	99.90%	100.00%	90.87%		99.41%
6MV WFF IMRT	3	94.16%	99.87%	91.53%		97.97%
10MV WFF IMRT	3	95.95%	98.27%	90.78%		97.88%
15MV WFF IMRT	3	96.22%	99.99%	81.46%		97.96%
6MV FFF Rapid Arc	2	100.00%	100.00%	86.82%		99.63%
6MV FFF Rapid Arc	1	86.59%	100.00%	83.51%		97.49%