A Novel End-to-End Test System in Assessing the Beam-by-Beam Delivery Accuracy for the CyberKnife® System

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Introduction

The geometric and dosimetric dose delivery accuracy is essential for a stereotactic radiosurgery system, and is required to be verified and maintained with quality assurance (QA) procedures performed on regular bases. Typical procedures test the delivery performance of the targeting system and beam shaping collimators. The current overall clinical delivery accuracy tests recommended by the vendor and routinely performed at each site for Cyberknife system are the End-to-End (E2E) tests which employ film measurement on a hidden target and AQA tests for daily performance consistency QA. The current film based End-to-End test verifies overall targeting accuracy on an isocentric delivery only. It neither provides beam-by-beam delivery accuracy nor the beam shaping accuracy. This report examines the use of the XRV-100 (Logos Systems, Scotts Valley, CA), a novel 3-D scintillator geometry and imaging system, to analyze the individual beams, and calculate the overall accuracy, of non-isocentric plans.

The XRV-100 phantom is composed of an imaging cone laminated with an x-ray scintillator phosphor, coupled with a sensitive CCD digital camera (*Figure 1)*. As each beam of radiation enters and exits the cone, it creates two spots of light by Compton scattering (*Figure 2*). During the radiation delivery, the CCD camera digitizes and the software records those spots in real-time along with the calculated values for the 3D beam vector, beam flux profile, and beam duration.

Fig. 1 – XRV-100 phantom with imaging cone shroud removed

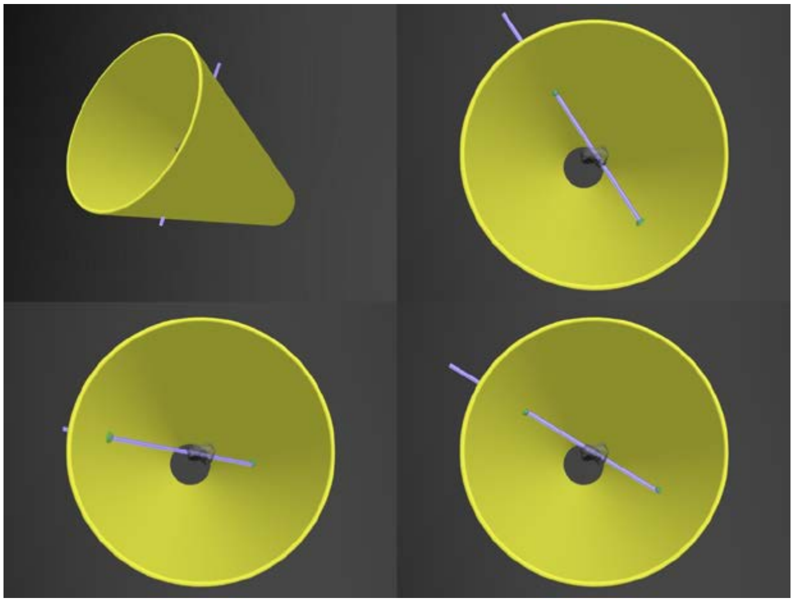


Figure 2 – Radiation beams passing through the XRV-100 scintillator cone create two spots of visible light

To perform either an isocentric or non-isocentric test, an *a priori* knowledge of the location of the intended target is required.

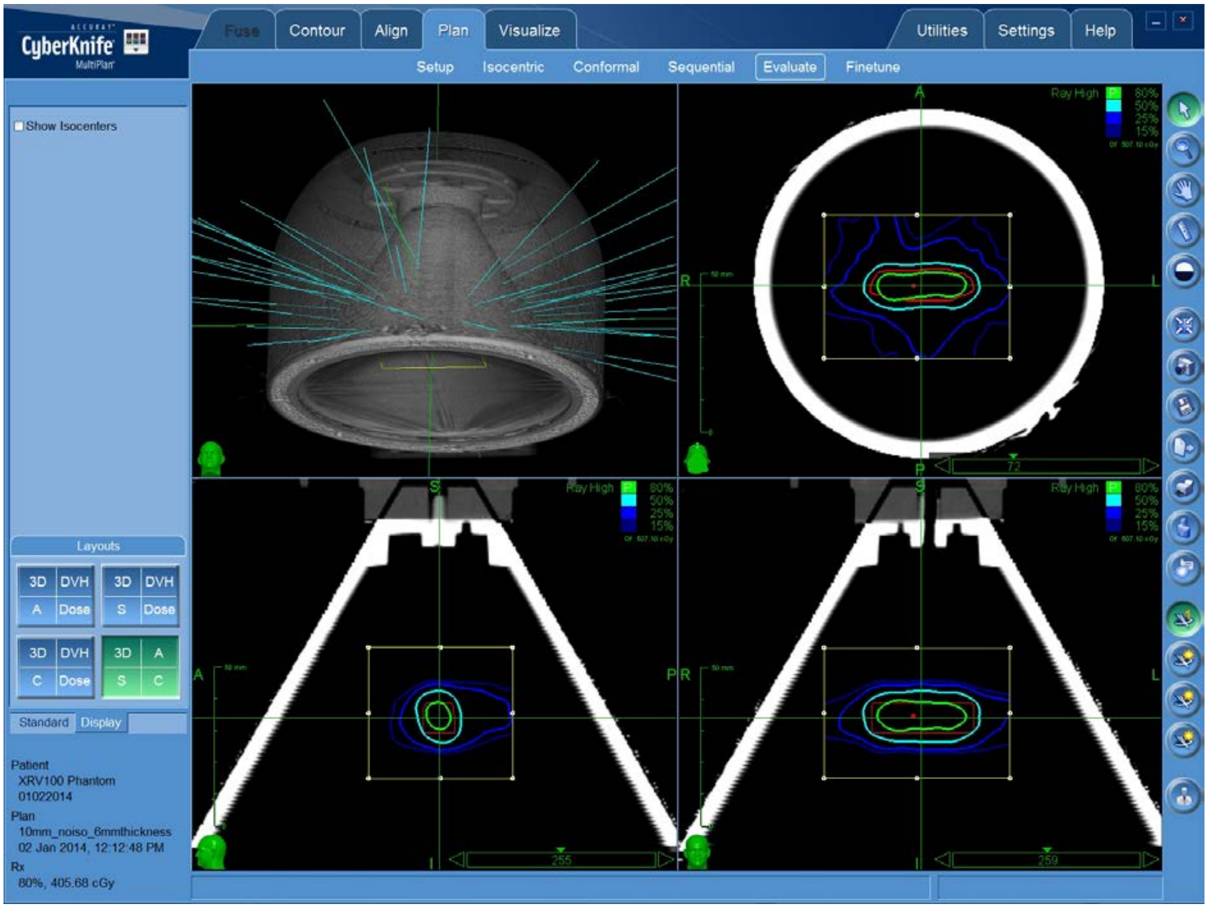
For an isocentric plan, there is a single XYZ target, so the accuracy of a beam path is a simple calculation. In a Winston-Lutz QA test, for example, there are typically two beams delivered at two angles: one is lateral, and the other is anterior-posterior. They are both aimed at the same XYZ target in 3D space.

For a non-isocentric plan, there are multiple XYZ targets that are defined by the treatment planning software, so the calculations are complex. This target “cloud” is made up of multiple beams, at multiple angles, covering a three dimensional volume. For CyberKnife systems, the beam node and target positions along with other plan data are contained in an XML file created by Multiplan.

With the XRV-100 VolumeWorks-CK software, the captured beam set is compared to the CyberKnife XML file, enabling the accuracy measurement of each beam in the delivered treatment plan. The delivery accuracy is defined as the 3D distance from where the CyberKnife robot is designed to aim and the actual position within the XRV-100 where the beam is detected.

Materials and Methods

The XRV100 phantom was first scanned with a CT scanner at 0.625 slice thickness and exported to the Cyberknife Multiplan (v4.6) treatment planning system. Two treatment plans were created with an approximately 1 x 1 x 2 cm^3 target in the middle of the XRV-100 imaging cone (*Figure 3*). Beams that did not produce both an entry and exit spot on the imaging cone were blocked during treatment planning to ensure that all the beams could be captured and measured. The two non-isocentric similar plans were created to deliver 900 cGy and 500 cGy maximum doses to the center of the target respectively. Each plan contained 40 non-isocentric and non-coplanar beams using a 10 mm fixed collimator.



Patient
XRV100 Phantom
01022014
Plan
10mm_noiso_6mmthickness
02 Jan 2014, 12:12:48 PM
Rx
80%, 405.68 cGy

Figure 3 – Multiplan view of the first 40 beam non-isocentric QA treatment plan

The XRV-100 was placed on the CyberKnife G4 system patient couch so that the kV imaging system had a clear view of the imaging cone fiducials (*Figure 4*). The CCD imaging camera in the phantom has a USB interface which was connected via an extension cable to the controlling laptop located outside the treatment room. There were no cables connecting the CyberKnife system to the XRV-100. All beam on/off triggering was detected by the image processing software residing on the laptop.

Figure 4—The XRV-100 phantom placed on the treatment couch

The plans were delivered on the Cyberknife G4 system with fiducial tracking using the four metal fiducials embedded near the apex of the cone (*Figure 4*). The image sequences were recorded in real-time during the delivery and quickly converted to disk measurements following delivery completion. Plan 1 was delivered once, and Plan 2 was delivered twice, to test the delivery reproducibility. The XRV-100 phantom was repositioned between the deliveries by changing the patient couch position several centimeters along each axis. This was done to ensure that the image guidance was performed independently between the three deliveries.

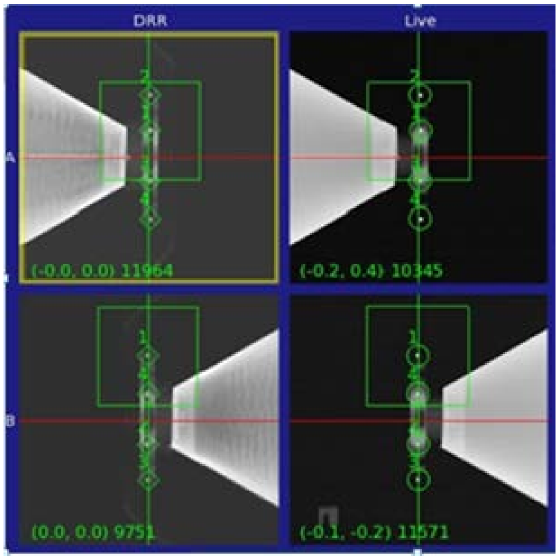


Figure 5— Fiducial tracking Digitally Reconstructed Radiographs and live images

The XRV-100 VolumeWorksCK software was used to read the XML beam list files produced by Multiplan and convert the beam vector source and target XYZ locations into the spherical coordinate system used by the XRV-100. This format features a single XYZ location which is the closest approach of the beam to the central axis of the imaging cone, along with angular coordinates Theta and Phi which define the beam delivery vector. This XYZ location is called the Isofocus in *Figure 6*. The location of the four imaging cone fiducials in the XML file were used to align the converted XML beam vectors to their corresponding locations in the XRV-100 reference frame.

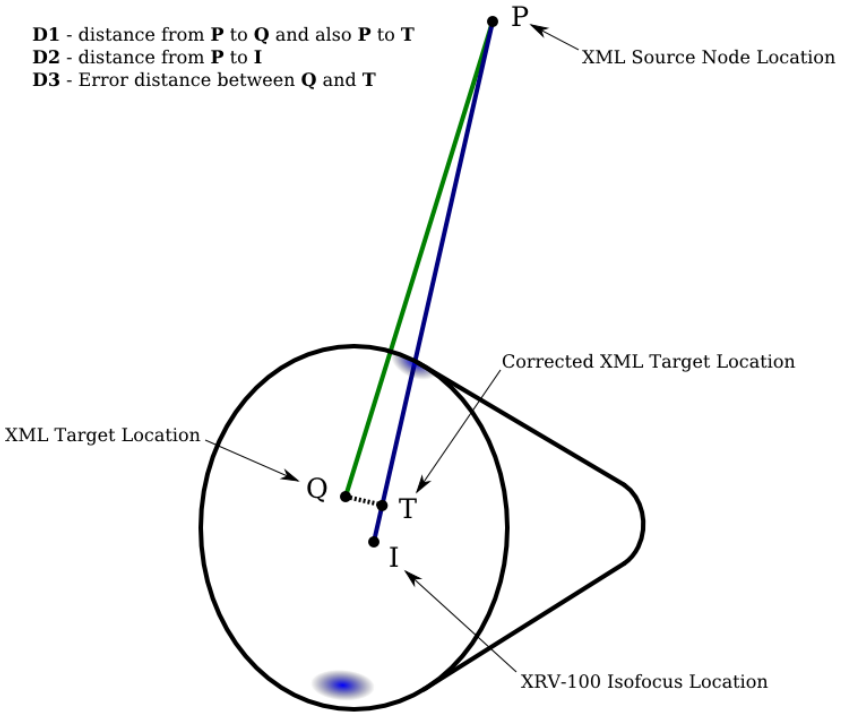


Figure 6 – Delivery Error Distance Calculation

A matching algorithm is employed so that only one XRV captured beam is assigned to its corresponding XML beam vector. Assignments can be quickly verified using the delivery sequence contained on the plan printout.

Matching is accomplished by calculating a distance function between each beam in both beam sets using differences in their respective Isofocus position, delivery angle (Theta and Phi), and diameter values. Matches are determined by those XML/XRV beam pairs that have a minimum value when their distance function value is compared to all other beam pairs.

Beam pair data, along with target versus delivery error distances, is then output to Excel as a formatted QA report. *Figure 6* shows a pictorial description of the algorithm used to calculate the delivery accuracy of each CyberKnife beam. Point I is the XYZ Isofocus location along the delivered beam that passes closest to the center axis of the cone. The Isofocus at Point I is calculated by the XRV-100 software using the entry and exit spot positions on the imaging cone signified by the blue ellipses in *Figure 6*.

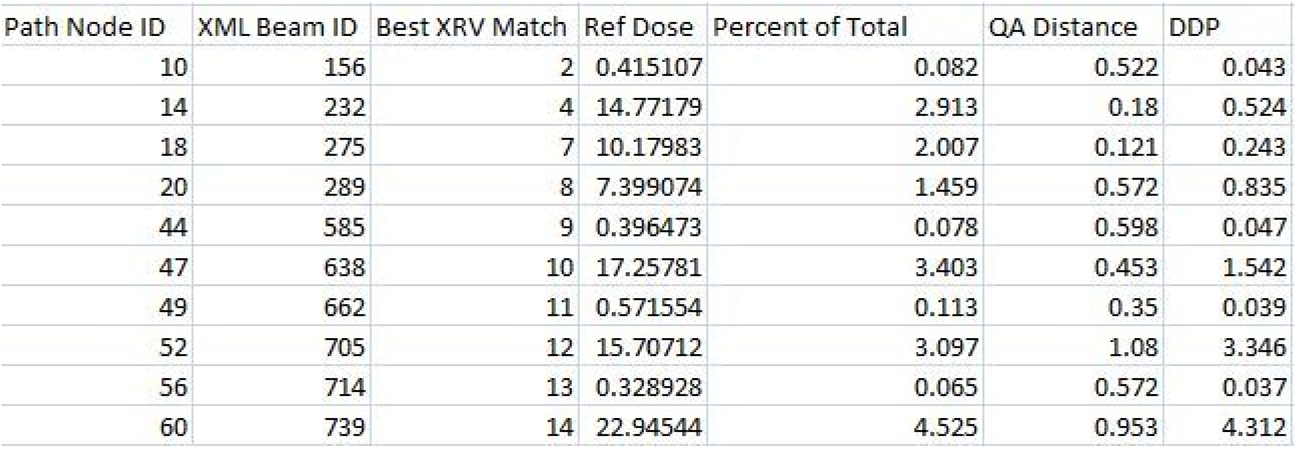
If there is no delivery error, the target location Q defined in the XML file should be located somewhere along the line starting at the XML source node location P and ending at the measured Isofocus I. The delivery targeting accuracy is defined as the XYZ distance from the XML target Q and the point T which lies on the beam path detected by the XRV-100. The lengths PQ and PT are assumed to be equal in order that the final numerical result is similar to the accepted industry concept of treatment margin. For the CyberKnife, error distance should typically be less than 1.0 mm.

The XML file data also enables the distance from the beam source P to the imaging cone entry spot to be calculated. Once that distance is known, the FWHM measurements of the beam entry spot can be scaled as if the entry spot is located at the nominal 800 mm used for CyberKnife water tank commissioning measurements.

Diameter measurements are made by first dewarping the camera’s view of the beam as it enters the cone into a new grayscale bitmap. Individual diameter measurements are made at 5 degree increments through the center of the dewarped entry beam bitmap using grayscale values that are half of the maximum brightness value. These 72 measurements are averaged to become the final beam diameter value that is normalized to 800 mm and then reported in the VolumeWorksCK QA report along with a comparison to commissioning values.

Results

The coordinates of the captured beam vectors in the XRV-100 data were successfully matched with their corresponding XML file coordinates for all three plan deliveries. Shown in *Figure 7* are the first ten XML beams from Plan 2 matched with Delivery A data.

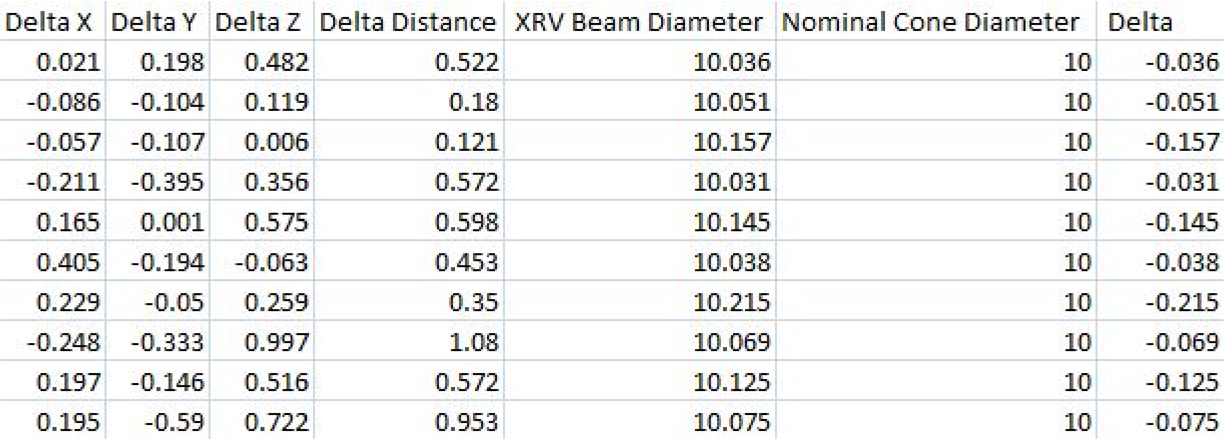


Path Node ID	XML Beam ID	Best XRV Match	Ref Dose	Percent of Total	QA Distance	DDP
10	156	2	0.415107	0.082	0.522	0.043
14	232	4	14.77179	2.913	0.18	0.524
18	275	7	10.17983	2.007	0.121	0.243
20	289	8	7.399074	1.459	0.572	0.835
44	585	9	0.396473	0.078	0.598	0.047
47	638	10	17.25781	3.403	0.453	1.542
49	662	11	0.571554	0.113	0.35	0.039
52	705	12	15.70712	3.097	1.08	3.346
56	714	13	0.328928	0.065	0.572	0.037
60	739	14	22.94544	4.525	0.953	4.312

Figure 7 – First 10 beams in Plan 2 XML file with corresponding XRV capture order

Overall beam targeting accuracy is shown in the QA Distance column. These values are the XYZ distances from where the CyberKnife robot was pointing to the actual positions where the beams were detected as per *Figure 6*. Targeting accuracy is more significant for those beams that represent a higher percentage of the total dose so the DDP (Dose Distance Product) column represents the Percent of Total times the QA Distance columns.

Figure 8 shows more detail how individual delta XYZ components form the Delta Distance column for the first 10 beams of Plan 2 Delivery A. Also shown are the diameters for each of the ten beams and how those diameters compared to the 10 mm fixed cone commissioning value. All values are in millimeters.



Delta X	Delta Y	Delta Z	Delta Distance	XRV Beam Diameter	Nominal Cone Diameter	Delta
0.021	0.198	0.482	0.522	10.036	10	-0.036
-0.086	-0.104	0.119	0.18	10.051	10	-0.051
-0.057	-0.107	0.006	0.121	10.157	10	-0.157
-0.211	-0.395	0.356	0.572	10.031	10	-0.031
0.165	0.001	0.575	0.598	10.145	10	-0.145
0.405	-0.194	-0.063	0.453	10.038	10	-0.038
0.229	-0.05	0.259	0.35	10.215	10	-0.215
-0.248	-0.333	0.997	1.08	10.069	10	-0.069
0.197	-0.146	0.516	0.572	10.125	10	-0.125
0.195	-0.59	0.722	0.953	10.075	10	-0.075

Figure 8 – Robot accuracy measurements for the first 10 beams in Plan 2 Delivery A

Robot positioning error for the CyberKnife is specified to be typically less than 1.0 millimeter. XRV-100 measurement accuracy is specified to be better than 0.2 millimeter, so the upper bounds for the measured Delta Distance (or QA Distance in *Figure 7*) is therefore approximately 1.2 millimeters.

Once the QA distances are calculated, statistics for the each delivery can be compiled and compared to other deliveries. The average overall delivery accuracies of the three deliveries are 0.63 ±0.25 mm, 0.66 ± 0.27 mm, and 0.60 ± 0.25 mm respectively. Max deviations for the three deliveries are 1.30 mm, 1.48 mm, 1.31 mm respectively. To assess the reproducibility, the coordinate differences of the two deliveries of Plan 2 are calculated. The average translational reproducibility is 0.14 ± 0.04 mm with most difference contributed from Z direction (0.11 ± 0.06 mm). This agrees with the fact of relative poor image resolution on digital reconstructed radiography (DRR) used for imaging guidance in this direction. Average reproducibility on Theta and Phi are 0.22 ± 0.01 degree and 0.00 ± 0.01 degree respectively.

The FWHM beam diameter data measured by the XRV-100 for Plan 2 Delivery A and B are summarized in *Figure 9*. The measured beam diameters are larger than the nominal cone diameter 10 mm by about 0.07 ±0.06 mm for all the beams, and by 0.04 ± 0.02 mm for the beams with less than 5 mm off axis distance. The measured FWHM was also found to increase slightly with the increase of off axis distance. This can be explained by the fact that those beams with larger off axis distance have to pass through thicker scintillator phosphor layers. The effect may be corrected in the future development.

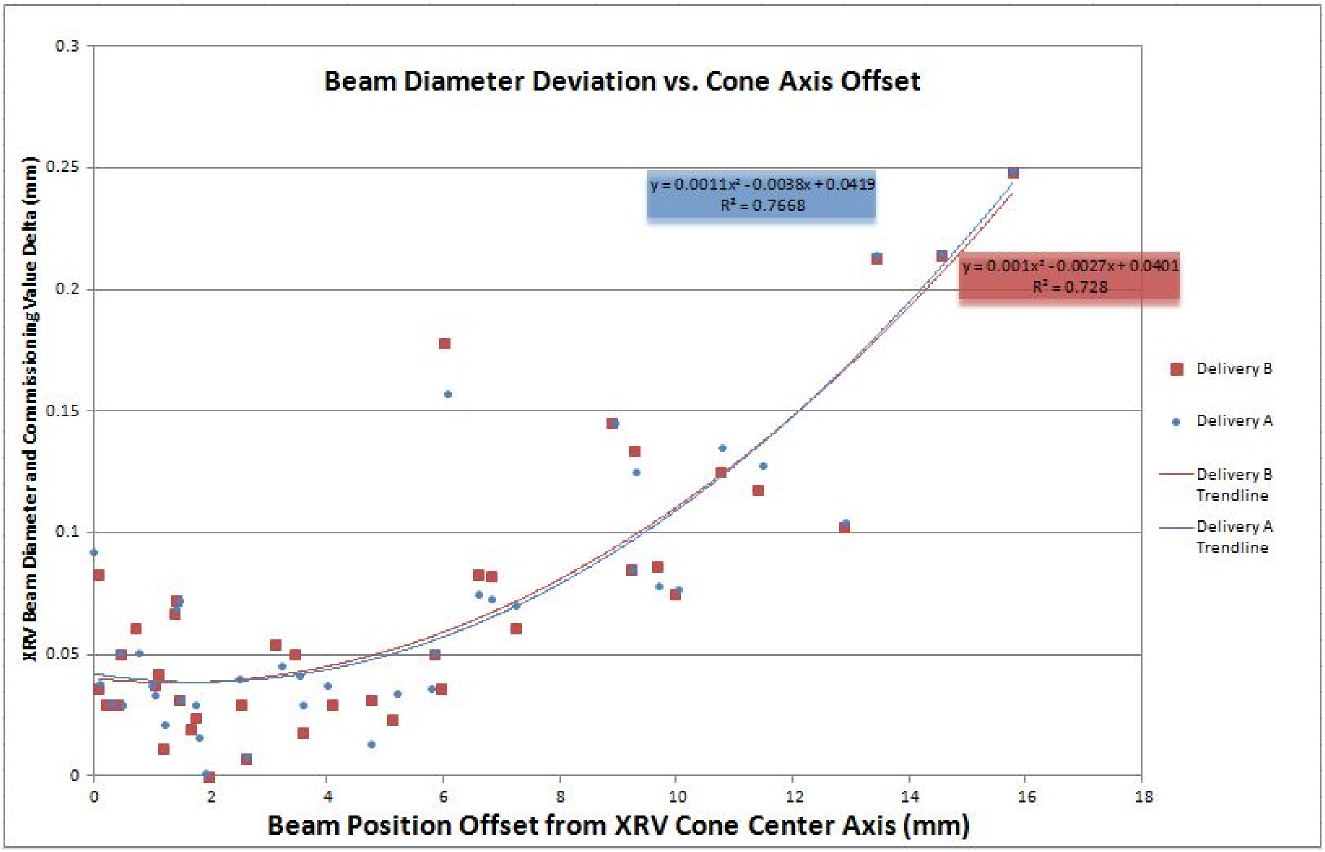


Figure 9 – XRV-100 versus Commissioning Value FWHM Measurements

Conclusion

The XRV-100 system is a powerful tool in performing end-to-end testing of Cyberknife treatment plan delivery. The experimental results agree with the stated sub-millimeter delivery accuracy of the Cyberknife system, and the high reproducibility in measurements verifies the stated 0.2 mm XRV-100 device accuracy. Compared with conventional film based end-to-end testing, this system provides beam-by-beam delivery accuracy for non-isocentric treatment plans, and thus is believed to be a more sensitive device for measuring machine performance deterioration. In addition to targeting accuracy, the XRV system also measures beam diameter within 0.1mm accuracy which may be a potential valuable QA tool for Cyberknife with Iris variable collimators.

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