A Novel Daily QA System for Robotic Image Guided Radiosurgery with Variable Aperture Collimator

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Introduction

This report examines the use of the XRV-100 (Logos Systems, Scotts Valley, CA), a novel 3-D scintillator geometry and imaging system, as a tool to perform a robust end-to-end daily quality assurance (QA) procedure for a robotic radiosurgery system (CyberKnife) with a variable aperture collimator (Iris).

One industry standard test employed for daily QA is adapted from the work of Winston-Lutz and employs two pieces of x-ray film exposed by anterior-posterior and lateral treatment beams. The main feature of the Winston-Lutz procedure is that it exercises the major radiosurgery subsystems in about 15-30 minutes providing a three-dimensional isocenter error distance. In this test, only two robot positions are verified for isocenter accuracy and no information is provided on the collimator performance. Other disadvantages include the cost of the x-ray film plus the time involved handling and scanning the film along with measuring the results.

A superior end-to-end daily QA procedure would include the verification of many clinically significant robot delivery angles and direct Full Width Half Maximum (FWHM) beam measurements using several collimator apertures. In addition, a more robust procedure should require no expendables (e.g. x-ray film) and be faster than the current Winston-Lutz test.

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

The XRV-100 phantom is composed of an imaging cone laminated with an x-ray scintillator phosphor, viewed by 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 captures images of those spots in real-time and the software calculates values for the beam three-dimensional position, vector angle, fluence intensity profile, and duration.

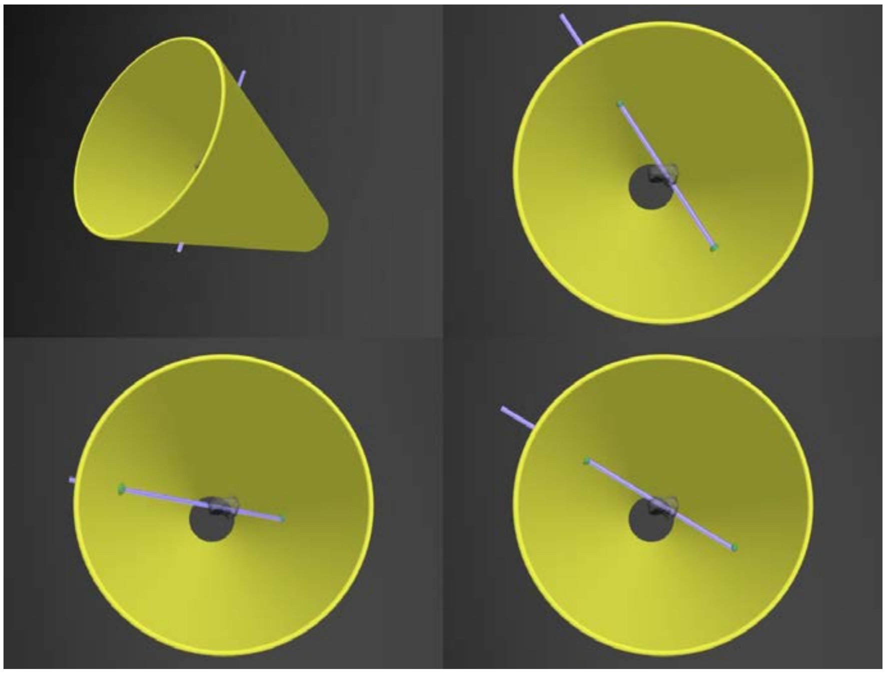

Figure 2 – Radiation beams passing through the XRV-100 scintillator cone create two spots of visible light

This report documents a ten beam treatment plan that was created for CyberKnife delivery to the XRV-100 for the purpose of daily QA. The beam vector and profile data captured during six plan deliveries spanning two separate days was then compared to the treatment plan beam list data and water tank commissioning measurements for consistency and accuracy.

Materials and Methods

The phantom was first scanned with a CT scanner at 0.625 mm slice thickness and exported to the Cyberknife Multiplan (v4.6) treatment planning system. An isocentric treatment plan was created consisting of ten beams of 25 Monitor Units each using Iris apertures of 7.5, 10, 15, 20, and 25 mm delivered to the center of the imaging cone (*Figure 3*).

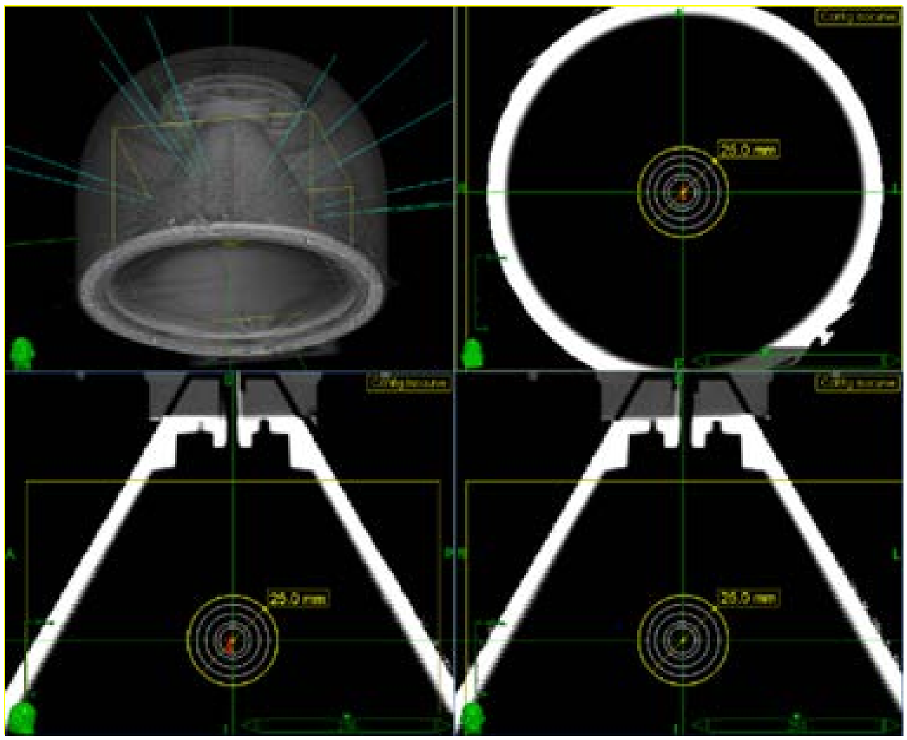

Figure 3 – Multiplan view of the 10 beam isocentric QA treatment plan

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 cable to the controlling laptop computer 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 plan was delivered six times in two days on the Cyberknife G4 system with fiducial tracking using the four metal fiducials embedded near the apex of the XRV-100 imaging cone (*Figure 5*). The image sequences were recorded in real-time during the delivery, converted to measurements and archived following delivery completion. 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 six deliveries.

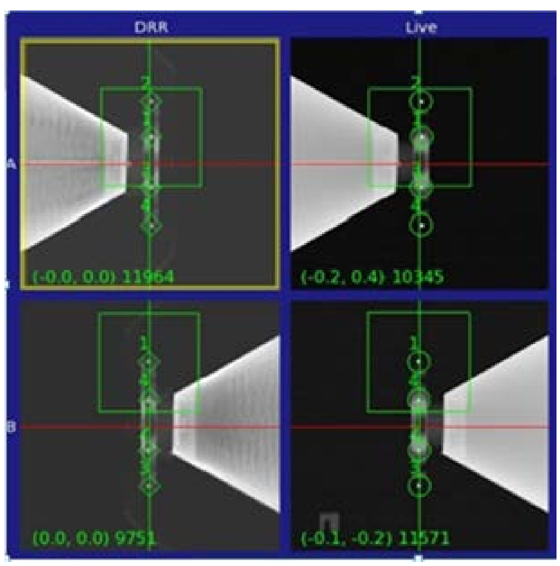

Figure 5—Fiducial tracking Digitally Reconstructed Radiographs and live images

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 called the isofocus along with angular coordinates Theta and Phi which define the beam delivery vector. The isofocus is the closest approach of the beam to the central axis of the imaging cone. 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.

A matching algorithm was employed to assign each XML beam its corresponding XRV-100 captured beam. This step is needed because the XML beam lists are not in delivery order. 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.

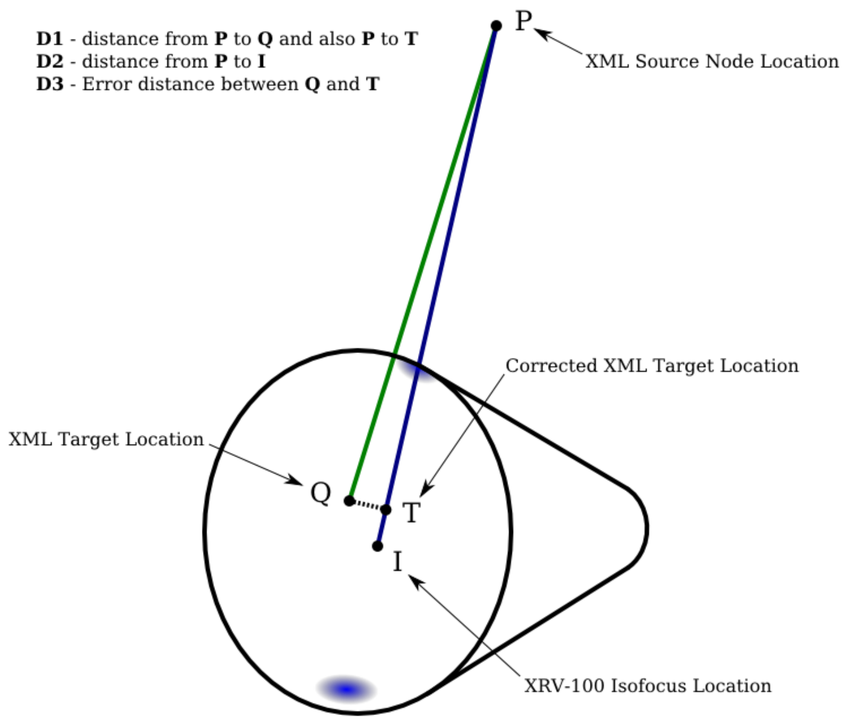

Figure 6 – Delivery Error Distance Calculation

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 error distance 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 error distance 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, the 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 QA report produced by VolumeWorksCK contains a summary section and a detailed beam-by-beam list of XML and XRV data. The summary for the first of the six treatment plan deliveries is shown below (*Figure 7*).

	A	B	C	D	E	F	G	H	I	J	K
1	VolumeWorksCK QA Report - V1.21										
2	File Name:	C:\BeamWorksDelta\Stanford_IrisQA\IRIS_AQA_5-25_plan.xml_VolumeWorksQAReport_2014_0324_0002.csv									
3	XML Source File:	C:\BeamWorksDelta\Stanford_IrisQA\IRIS_AQA_5-25_plan.xml									
4	XRV Source Folder:	C:\BeamWorksDelta\Stanford_IrisQA\IRIS_AQA_5to25_DeliveryA									
5	Match Type:	Any Order									
6											
7	Matched Total Dose (cGy):	174.943									
8	Total Dose (cGy):	174.943									
9	Percent:	100									
10	XML Beam Match Count:	10	Out of:	10							
11	Average QA DeltaX Y Z (mm):	0.305	0.309	0.486	Average QA Distance	0.712					
12	XRV Beams Not Matched:	0									
13											
14	Max Dose Distance Product:	12.151	9.729	8.422	7.937	7.934					
15	XML Beam ID:	226	135	191	18	175					
16	QA Distance (mm):	1.554	0.965	0.904	0.778	0.834					
17	Max DDP (Top 5) Percent of Total Dose:	46.935									
18											
19	Max QA Distance (mm):	1.554									
20	XML Beam ID:	226									
21											
22	Total Number of Captured XRV Frames:	326									
23											
24	Iris Collimator Aperture QA										
25	Average FWHM delta from Commissioning Values (mm):	0.096									
26	Maximum FWHM delta from Commissioning Values (mm):	0.275									

Figure 7 – QA Report Summary for Delivery A

Using the Delta Distance column listed in the beam-by-beam section of the QA report (*Figure 8*), the average error distance for the first treatment plan delivery is 0.71 ±0.40 mm. The targeting accuracy for the other five deliveries are 0.72 ± 0.44 mm, 0.74 ± 0.42 mm, 0.70 ± 0.40 mm, 0.79 ± 0.44 mm and 0.69 ± 0.41 mm respectively.

Delta X	Delta Y	Delta Z	Delta Distance
-0.176	-0.149	0.206	0.309
-0.208	-0.342	-0.334	0.521
-0.152	0.455	0.612	0.778
-0.011	0.074	0.378	0.386
-0.27	0.602	0.509	0.834
0.313	0.542	1.422	1.554
-0.459	0.722	0.447	0.965
0.534	-0.105	-0.463	0.714
0.127	0.036	0.071	0.15
0.8	0.067	-0.416	0.904

Figure 8 – Targeting Accuracy Detail for Delivery A in millimeters

Robot beam pointing error for the CyberKnife is specified to be typically less than 1.0 millimeter at the nominal SAD of 800 mm. XRV-100 measurement accuracy is specified to be 0.2 millimeter or better, so an approximate upper bounds for the targeting accuracy would therefore be 1.2 millimeters.

Beam 6 in the delivery order consistently had the maximum Delta Distance of each data set with an average of 1.58 mm. One unique characteristic of this beam is that the CyberKnife robot leans over completely on its side for the specified lateral delivery.

The differences between the distance normalized FWHM beam diameters and commissioning values for the first delivery are shown below (*Figure 9*). For all six deliveries the average difference between commissioning values and the XRV beam diameter measurement is 0.11 mm. Each of the ten FWHM diameter measurements are very consistent with the standard deviation for each group of six measurements being 0.03 mm or less. Maximum excursions for each group were within ±0.04 mm of their respective average.

XRV Beam Diameter	Iris Commissioning Value (closest)	Delta
24.678	24.73	0.052
14.704	14.58	-0.124
19.823	19.69	-0.133
24.869	24.73	-0.139
9.756	9.67	-0.086
7.264	7.29	0.026
14.855	14.58	-0.275
7.236	7.29	0.054
19.757	19.69	-0.067
9.673	9.67	-0.003

Figure 9 – Captured Beam Diameters versus Iris Collimator Commissioning Values in millimeters for Delivery A

The Iris collimator control mechanism has a specified accuracy of ±0.1 mm which at 800 mm becomes ±0.2 mm. Beam 7 in the delivery order was a consistent outlier in each treatment plan delivery. This beam is on average 0.30 mm larger than the commissioning value with a standard deviation of 0.02 mm. This 0.30 mm average delta is about three times the overall delta value of 0.11 mm but is still within the 0.4 mm spread allowed by the Iris control system.

This ten beam treatment plan required 7 minutes for delivery. The XRV-100 software captured all camera images memory in real-time at 20 frames per second and upon completion of delivery, converted the beam images to measurement data in less than 60 seconds.

Conclusion

The experimental results agree with the stated sub-millimeter delivery accuracy of the Cyberknife robot. Beam diameter FWHM measurements comply with the 0.2 mm accuracy of the Iris collimator at the nominal SAD of 800 mm.

These results indicate that the XRV-100 system can be used to systematically assess the Cyberknife delivery accuracy as well as the consistency of the Iris beam aperture control system for treatment fields up to 25 mm in diameter.

The whole procedure can be performed within 10 minutes with instant results and trend lines available. Because it exercises the subsystem components more thoroughly and quickly, it is a superior tool for daily CyberKnife QA.

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