CyberKnife Iris Beam QA using Fluence Divergence

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Introduction

The CyberKnife radiosurgery system produces a pencil-thin beam of radiation that is aimed at the cancer tumor from many different angles during the course of a treatment. The Iris collimator used on over half of the CyberKnife systems is a mechanism consisting of 12 tungsten leaves that shapes the diameter of this beam as it diverges toward the patient. Understanding how the radiation beam diverges is useful in verifying that the treatment plans given to a patient are adequately painting the 3D volume of the lesion with radiation and missing nearby vital organs and healthy tissue. This report examines the use of a scintillator-based camera system to measure the CyberKnife X-ray fluence at several distances along the beam path, with analysis of the results.

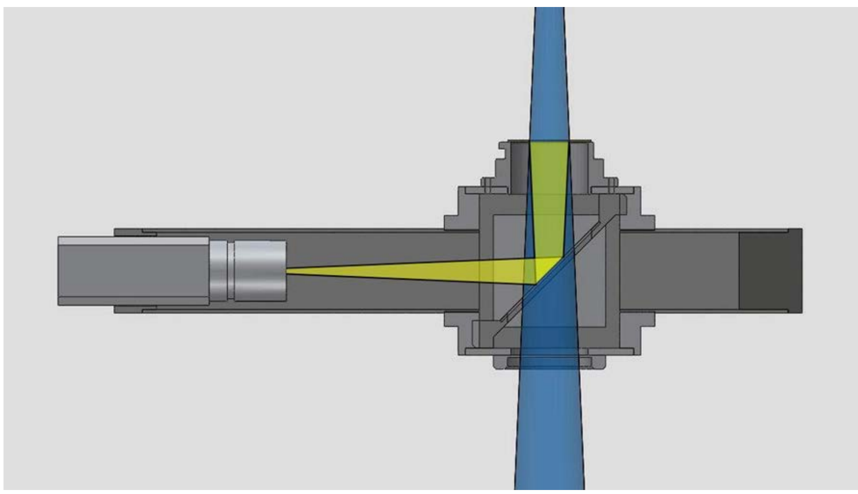

Figure 1 – The IBAC converts X-ray beam fluence (blue) to visible light (yellow) using a scintillator module

The Iris Beam Aperture Caliper (IBAC) made by Logos Systems (Scotts Valley, CA) consists of a darkened optical enclosure that directly attaches to the CyberKnife Iris. The IBAC allows a module holding X-ray scintillator phosphor to be inserted in the beam path directly below the Iris collimator. As ionizing radiation passes through the scintillator, a beam spot of visible light is formed by Compton scattering. This image is reflected by a mirror toward a digital camera and computer which can be used to measure the intensity profile of the beam diameter to an accuracy of .05 mm.

The Iris shapes the radiation into a dodecagon that approximates a circle and is capable of 12 different beam diameters: 5, 7.5, 10, 12.5, 15, 20, 25, 30, 35, 40, 50, and 60 mm. These beam diameters are typically measured 80 centimeters from the linear accelerator source or 80 cm SAD (Source to Axis Distance). The lower set of six collimator leaves where the fluence exits the Iris is located 40 cm from the beam source. Consequently, beam diameters measured at the lower collimator surface are presumed to be half of their 80 cm SAD values. The real-time feedback system that controls the Iris aperture has an accuracy of +/- 0.1 mm at the lower collimator and consequently +/- 0.2 mm at 80 cm SAD.

Materials and Methods

The IBAC camera enclosure was attached to the CyberKnife Iris as shown in *Figure 2*. The controlling laptop was placed near the CyberKnife control console and a USB extender cable was used to connect the laptop to the IBAC.

Figure 2 – The IBAC is shown attached to the CyberKnife Iris with the scintillator module access door open.

The IBAC is supplied with a calibration module that has a series of precisely aligned 1 mm holes that serve to calibrate camera pixel measurements to physical distances. The calibration module shown on the right in *Figure 3* is designed to be inserted through an access panel in the column of the IBAC and is held in place next to the lower Iris collimator by a series of magnets. With the Iris fully opened, the X-ray beam excites the scintillator material behind the mask forming a pattern of bright spots.

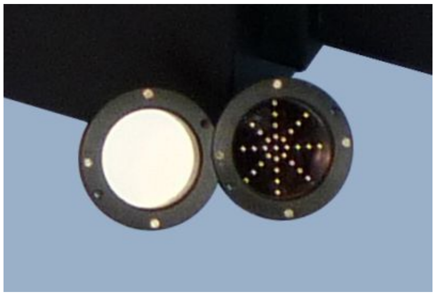

Figure 3 – Scintillator and calibration modules are held near the lower collimator using magnets

Figure 4 shows how the software finds the position of each spot formed by the calibration module mask pattern. The software uses the position and spacing of the spots to generate horizontal and vertical scaling ratios to convert pixel measurements into millimeters.

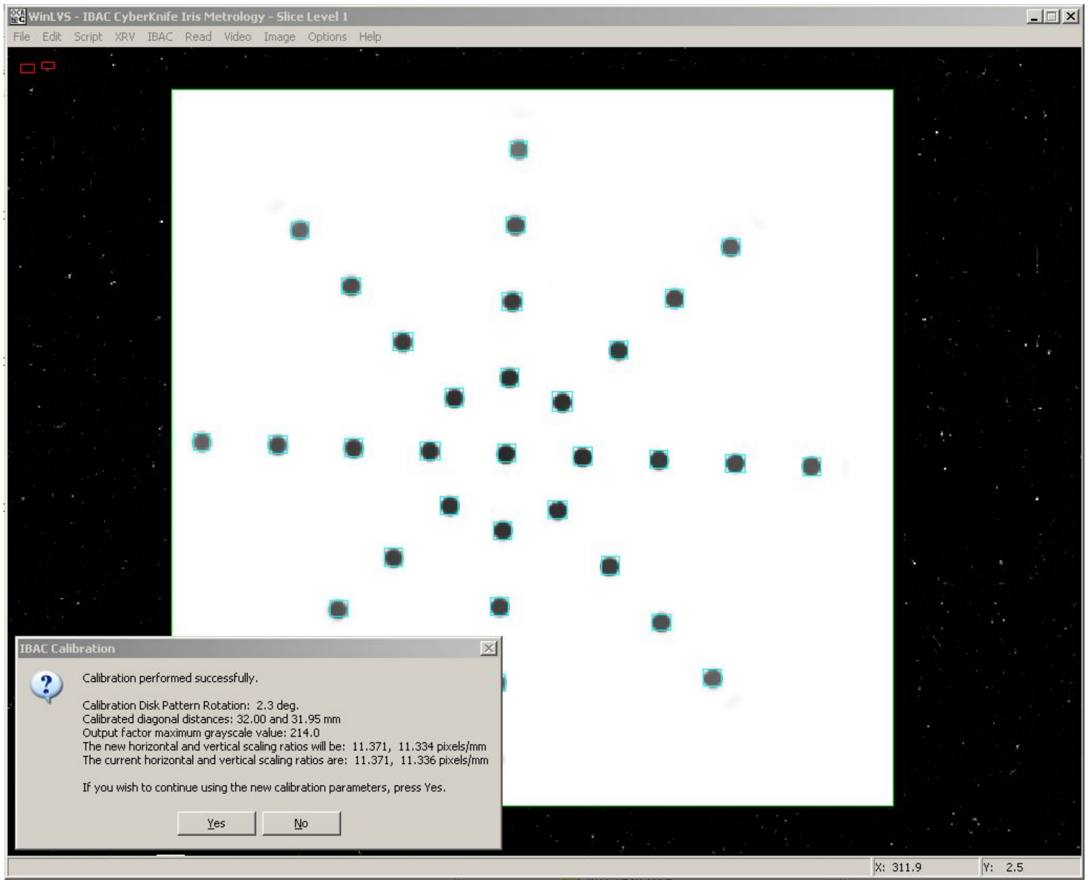

Figure 4 – IBAC calibration reference hole measurements

After the IBAC software was calibrated, a script was executed that waited for the presence of a beam spot in the camera's field of view. Once a beam was detected, 30 frames were integrated together to form an image having a superior signal-to-noise ratio than each individual frame. The beam spot in this integrated image was then measured over many different diameters and the average diameter saved to the measurement output file. Each integrated beam image was archived as an individual image file after measurement. Simultaneous to this script running, the CyberKnife was instructed to cycle through all 12 aperture sizes, exposing the IBAC for 50 Monitor Units at each aperture.

Next the IBAC was detached from the Iris and placed on a cart directly under the Iris as shown in *Figure 5*. The laser was used to adjust the position of the cart so that the radiation beam was pointed directly at the center of the scintillator module. The distance from the scintillator to the lower collimator surface was measured at 17.7 cm. Since the lower collimator is 40.0 cm from the source, the scintillator at this position is 57.7 cm from the source. A series of 12 beam sizes was captured at this position.

Figure 5 – IBAC detached from the Iris with the scintillator at 57.7 cm SAD

Two other sets of beam diameters were captured at 52.7 cm and 47.7 cm using 5 cm thick spacers placed beneath the IBAC. The 47.7 cm position is shown in *Figure 6*. During the three sets of measurements with the IBAC disconnected from the Iris, the beam passed through an extra 3 mm of rubber which was used to keep the enclosure darkened.

Figure 6 – IBAC supported by two 5 cm spacers with the scintillator at 47.7 cm SAD

Data Representation

IBAC beam diameters are measured using a full-width half-maximum (FWHM) algorithm. First the maximum and minimum grayscale intensities of the beam spot are used to determine the grayscale value that represents the half-maximum value. Next, the circular group of pixels that most closely match this grayscale midpoint are identified by the software and the center point is determined. Radii are then calculated every 5 degrees around this circle and these seventy-two values are used to calculate the average beam diameter. This value is recorded in the output text file or displayed in the beam viewer as shown in *Figure 7*.

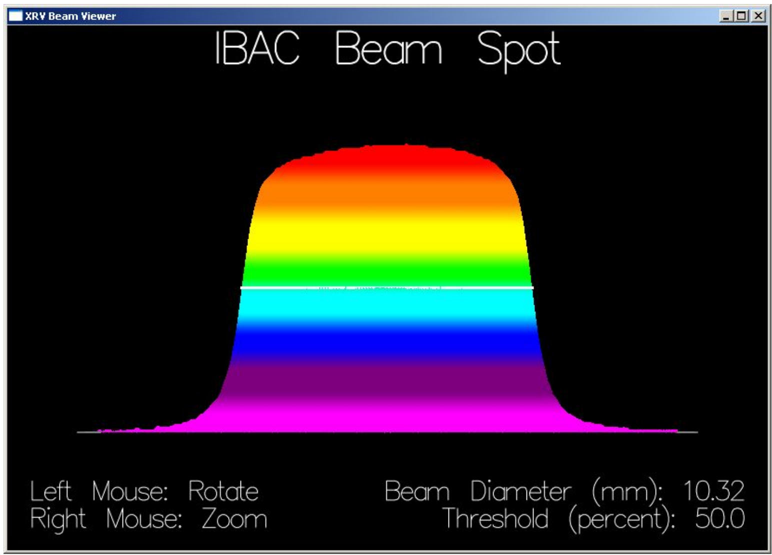

Figure 7 – IBAC beam profile for a 20 mm Iris aperture

Shown below is the script output text for the first 4 beam spot sizes with the IBAC attached to the Iris (40 cm SAD).

```
WinLVS Script Version:, 9.02,Time-Date:,11:04:43 02/03/2012,Center XY:,  325.177, 241.795
BWS,1,
Time,11:05:04 02/03/2012
1,Beam Spot Metrics,Units:,mm - percent, Diameter:,    2.60, Quality:,  93.95, Min. Gray:,   0.00, Max.
Gray:,  81.00, Output Factor:,   0.00
Time,11:05:07 02/03/2012,30
Time,11:06:17 02/03/2012
2,Beam Spot Metrics,Units:,mm - percent, Diameter:,    4.19, Quality:,  96.21, Min. Gray:,   0.00, Max.
Gray:,  91.00, Output Factor:,   0.00
Time,11:06:21 02/03/2012,30
Time,11:07:04 02/03/2012
3,Beam Spot Metrics,Units:,mm - percent, Diameter:,    5.41, Quality:,  97.89, Min. Gray:,   0.00, Max.
Gray:,  95.00, Output Factor:,   0.00
Time,11:07:08 02/03/2012,30
Time,11:07:55 02/03/2012
4,Beam Spot Metrics,Units:,mm - percent, Diameter:,    6.62, Quality:,  97.92, Min. Gray:,   0.00, Max.
Gray:,  97.00, Output Factor:,   0.00
Time,11:07:58 02/03/2012,31
```

Test Results and Analysis

The complete IBAC data using the four different SAD positions and twelve aperture sizes are shown in *Figure 8*. It can be seen that beam width measurements at 40.0 cm SAD are close to half the 80 cm SAD aperture sizes. Also note that beam diameters steadily increase along with distance from the source. The IBAC maximum field of view is 34.5 mm, so divergence measurements were limited with the 50 and 60 mm apertures. For QA purposes, the measured values at 40 cm for these two apertures when doubled are within tolerance of the expected 80 cm SAD values.

	5 mm	7.5 mm	10 mm	12.5 mm	15 mm	20 mm	25 mm	30 mm	35 mm	40 mm	50 mm	60 mm
40.0 cm SAD	2.6	4.19	5.41	6.62	7.85	10.32	12.75	15.23	17.62	20.04	24.97	29.92
47.7 cm SAD	3.13	5.06	6.5	7.93	9.41	12.3	15.19	18.06	20.86	23.73	29.56	Max.
52.7 cm SAD	3.47	5.56	7.17	8.79	10.37	13.57	16.69	19.88	22.98	26.14	32.59	Max.
57.7 cm SAD	3.87	6.11	7.88	9.6	11.39	14.86	18.29	21.79	25.17	28.67	Max.	Max.

Figure 8 – IBAC beam width measurements at 4 different distances to source

Shown in *Figure 9* is a chart of the data in *Figure 8* demonstrating that the IBAC has measured a good linear relationship between each beam diameter and its distance from the source of the X-ray fluence.

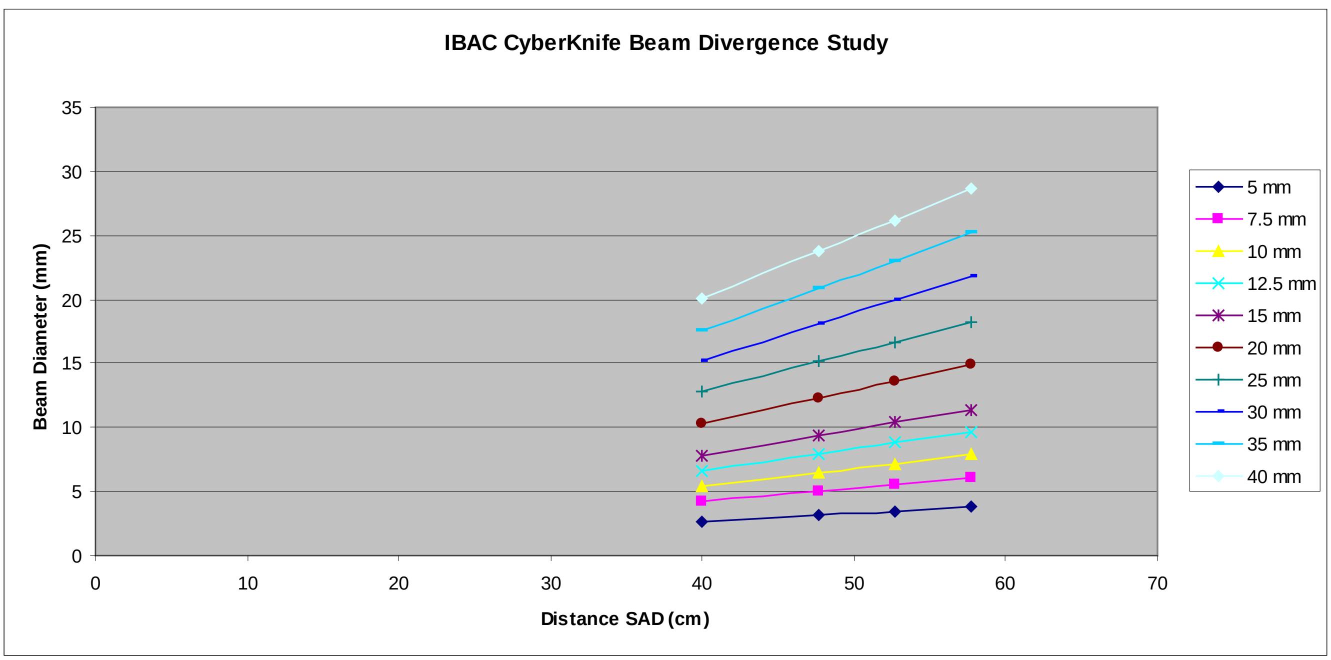

Figure 9 – Chart of IBAC measured beam spot diameters at the 4 SAD positions

Figure 10 applies linear regression to the data and displays the formula in slope intercept format for each set of aperture measurements.

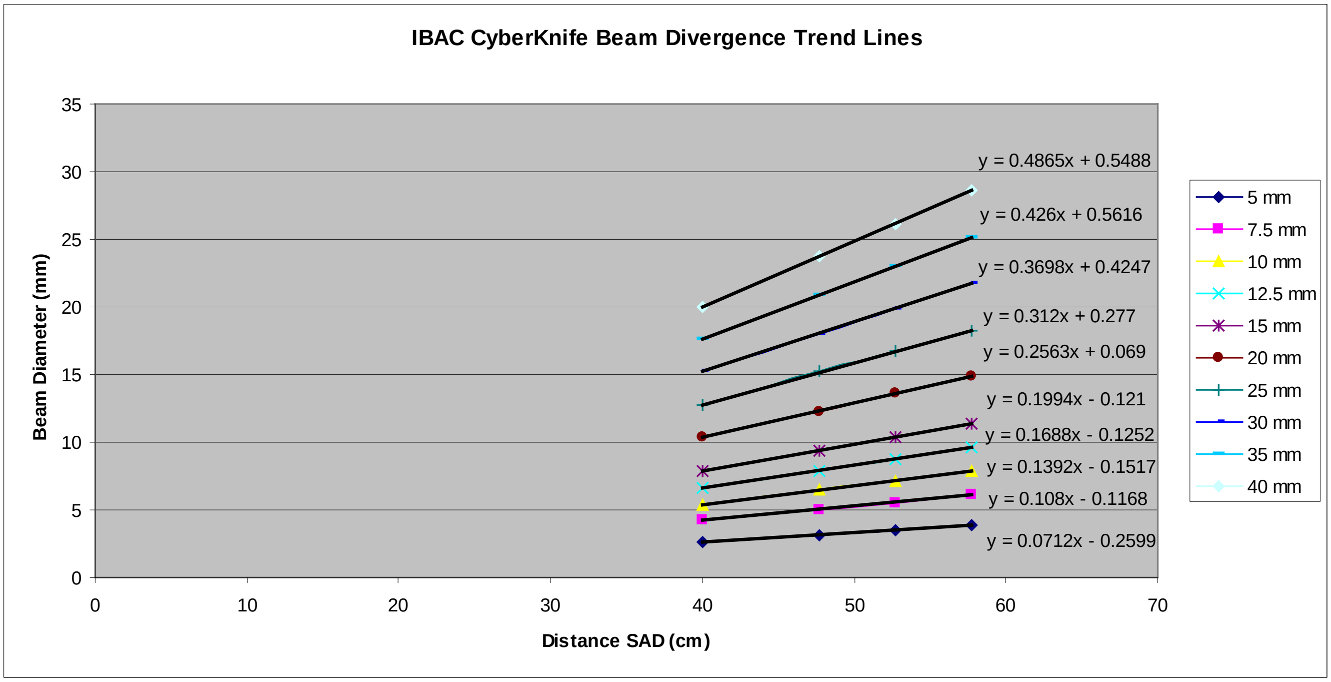

Figure 10 – Linear regression analysis applied to all beam diameter trends

Figure 11 contains the linear regression coefficients calculated in the previous chart with slope being the m value and intercept the b value in the equation y = mx + b. In this equation y is the beam diameter in millimeters at the distance x centimeters from the source. These coefficients are then used to calculate the expected beam fluence diameter at 80 cm SAD. In the dose domain, the beam diameter at 80 cm SAD is expected to be close to the selected aperture size, and so the far right columns calculate the difference between the projected fluence beam widths and the expected 5 mm to 40 mm dose beam width at 80 cm.

Aperture (mm)	Linear Regression Beam Divergence			Expected Width	Dose Width	Delta
	Slope	(Degrees)	Intercept	at 80 cm SAD (mm)	Delta (mm)	Percent
5	0.0712	.4079	-0.2599	**5.4361**	0.4361	8.722
7.5	0.108	.6188	-0.1168	**8.5232**	1.0232	13.64267
10	0.1392	.7975	-0.1517	**10.9843**	0.9843	9.843
12.5	0.1688	.9671	-0.1252	**13.3788**	0.8788	7.0304
15	0.1994	1.142	-0.121	**15.831**	0.831	5.54
20	0.2563	1.468	0.069	**20.573**	0.573	2.865
25	0.312	1.787	0.277	**25.237**	0.237	0.948
30	0.3698	2.118	0.4247	**30.0087**	0.0087	0.029
35	0.426	2.439	0.5616	**34.6416**	-0.3584	-1.024
40	0.4865	2.785	0.5488	**39.4688**	-0.5312	-1.328

Figure 11 – Linear regression coefficients used to predict beam fluence diameter at 80 cm SAD

It should be noted that the CyberKnife linear accelerator radiation source is formed by a beam of electrons approximately 3 mm in diameter striking a tungsten plate. A rigorous analysis of the intercept values for the beam apertures should take into account the fact that the beam starts not as a point, but as a disk 3 mm in diameter. It should also take into account the mechanical design of the upper and lower Iris collimator banks and the distance that separates each bank from the source. For the purpose of this paper, the Iris is treated as a "black box" and only the characteristics of the emerging X-ray fluence are discussed.

The most concerning data in *Figure 11* are the projected 80 cm SAD beam fluence diameters for the 7.5 and 10 mm aperture sizes. These values are 1.02 and 0.98 mm larger than their corresponding nominal dose values. Their percentage differences of 13.6% and 9.8% percent from nominal are the largest of all the aperture widths. These deviations should be investigated more thoroughly as part of regular Iris QA procedures. Another alternative would be to take new water tank dose profile measurements and compare those profiles to commissioning values looking for any out-of-tolerance beam diameter increases.

Conclusion

The beam fluence divergence angles in air for ten of the Iris apertures have been measured. The extrapolated beam diameters at 80 cm SAD serve as a QA benchmark for comparing these fluence beam measurements with those made using traditional ion chamber and diode dose-based methodologies. At least two of these extrapolated beam diameters indicate the need for additional dose beam width verification with commissioning values.

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