

WAYNE STATE
UNIVERSITY

SCHOOL OF MEDICINE

A Systematic Analysis of the Error
Sources within the CyberKnife M6 Daily
AQA Test

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Agenda

1. Objective
2. CyberKnife M6 Overview
3. CyberKnife AQA Explained
4. Methods
5. Results
6. Conclusion
7. Acknowledgements & References
8. Questions

Objective

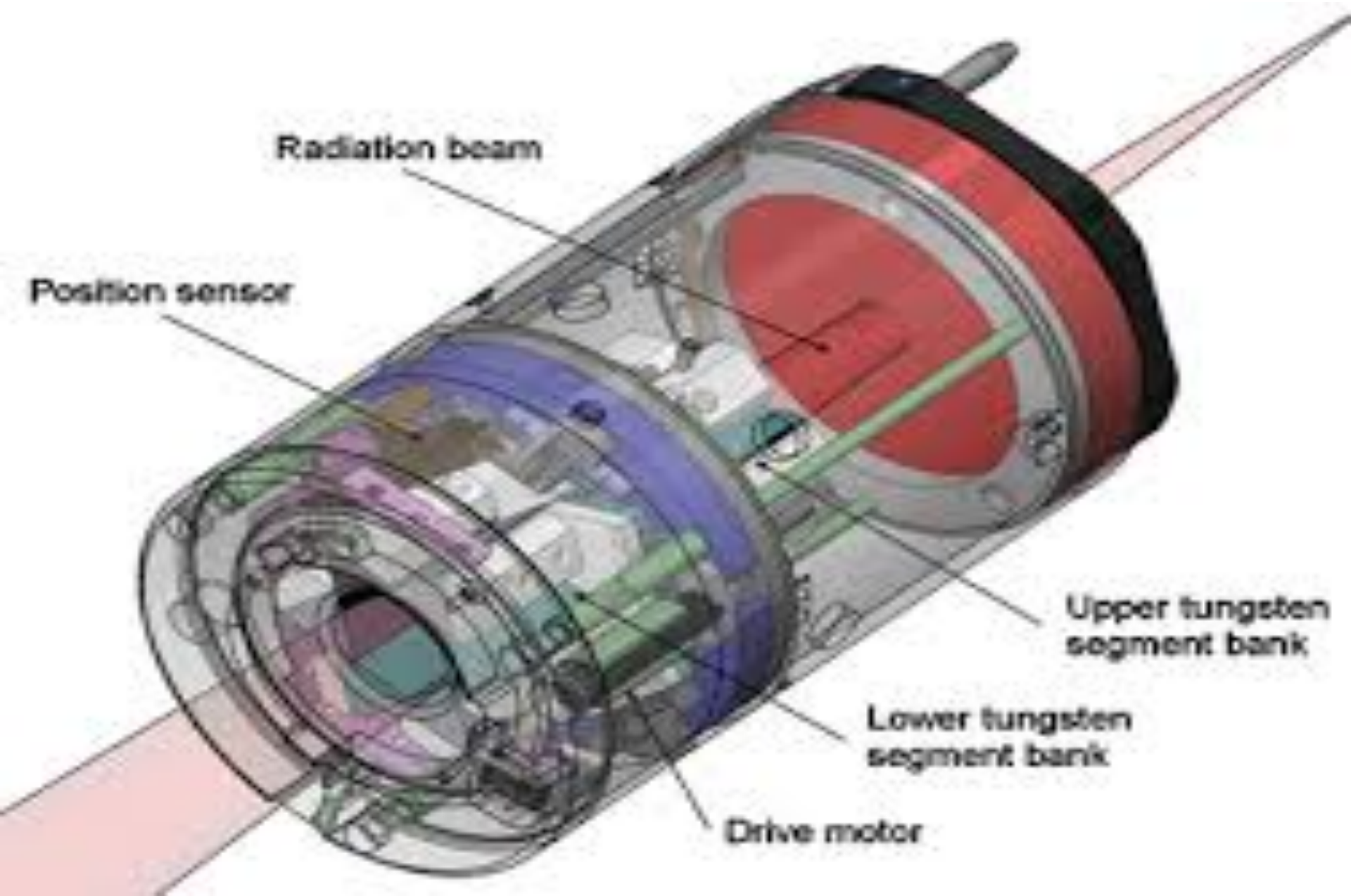
To determine and critically analyze the sources of error within the daily Automatic Quality Assurance (AQA) test used on the CyberKnife M6 system.

CyberKnife Overview

AAPM TG-135: Quality Assurance for Robotic Radiosurgery

- Purpose (2011)
 - (1) Make QA code of practice
 - (2) Recommendations on techniques
 - (3) Issues needing further R&D
- Procedures
 - Stereotactic Radiosurgery (SRS)
 - Trigeminal Neuralgia: 80-90Gy, x1 fraction
 - Stereotactic Body Radiation Therapy (SBRT)
 - 6-30Gy, x1-5 fractions
- CyberKnife System Accuracy: < 1mm





Radiation beam

Position sensor

Upper tungsten segment bank

Lower tungsten segment bank

Drive motor

CyberKnife Overview

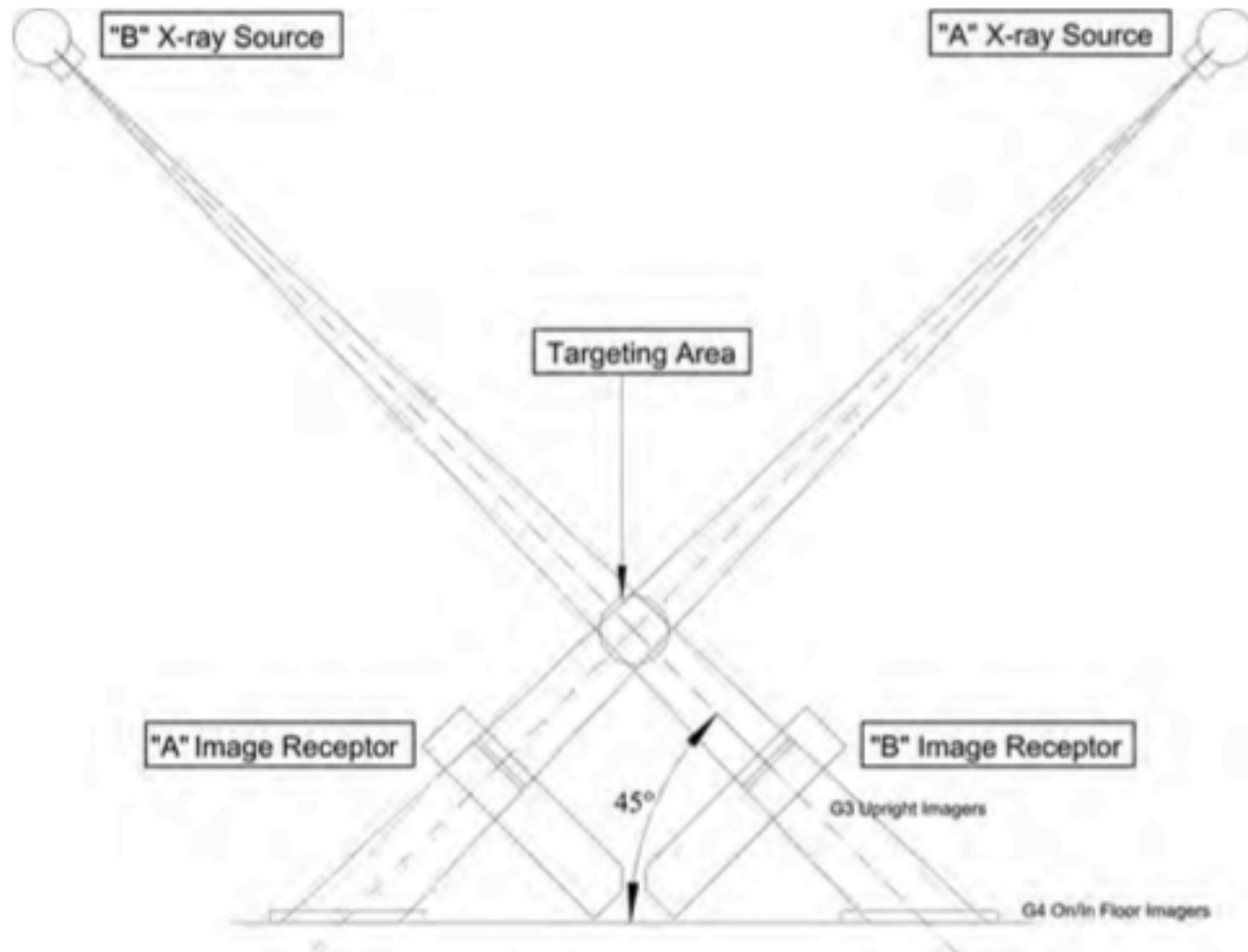


FIG. 2. Image Geometry of image-guidance x-ray system. This view has the observer standing at the head of the couch looking toward the patient.

CyberKnife Overview

- **GAFChromic EBT3**
 - 1cGy to >40Gy

Matte Polyester, 120 μm

Active Layer, ~28 μm

Matte Polyester, 120 μm

EBT3 and EBT3+

CyberKnife Overview

- **Auto QA**
 - 2cm Tungsten
 - Eccentricity
 - Shadow

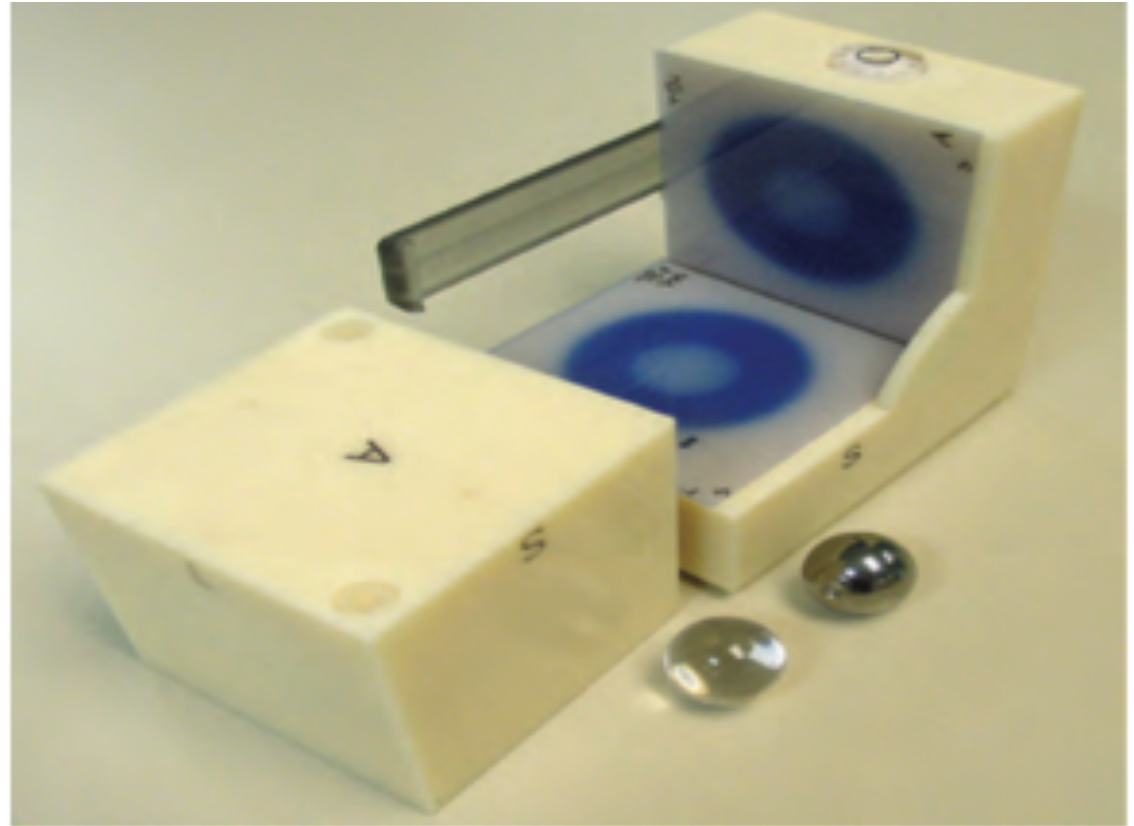


FIG. 8. The AQA phantom showing the orthogonal films after exposure. The clear plastic ball is inserted for the CT scan and replaced by the tungsten ball for the Winston-Lutz test. Figure courtesy of Accuray Inc.

Select Image...

Browse

Process

Image A
Inf

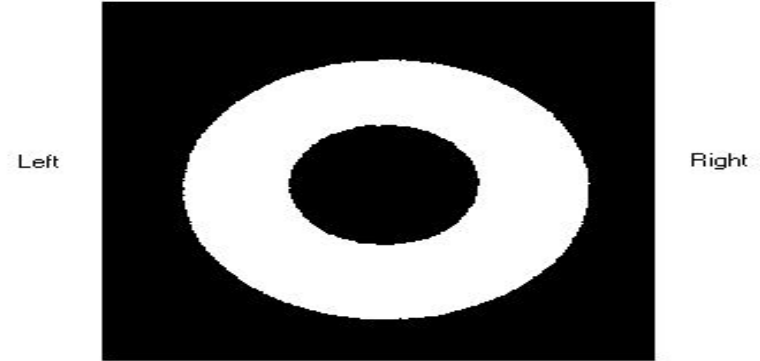
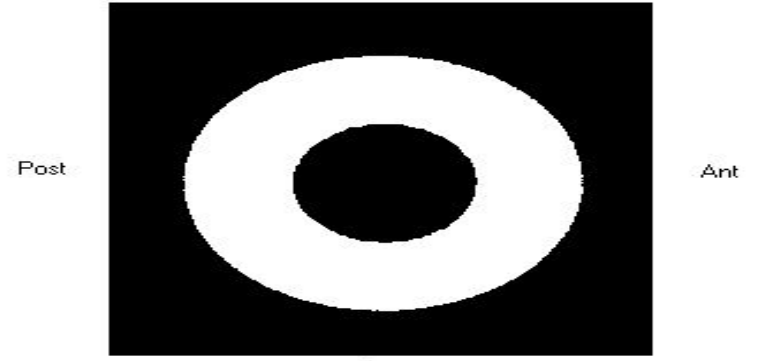


Image B
Inf



Notes:
 Reproducibility_1

Date:
 14-Aug-2014

Time:
 13:19:11

Image A Coordinates

X centroid offset : 0.25208 mm
Y centroid offset : 0.78722 mm

Eccentricity (Beam) : 0.10401
Eccentricity (Shadow) : 0.14379

Image B Coordinates

X centroid offset : -0.17215 mm
Y centroid offset : -0.0054011 mm

Eccentricity (Beam) : 0.091537
Eccentricity (Shadow) : 0.11014

Average Center Pixel Intensity : 28692
 (Coarse Estimate)

Patient Plane Coordinates

X offset : -0.39091 mm
 (superior-inferior)

Y offset : -0.25208 mm
 (right-left)

Z offset : -0.17215 mm
 (posterior-anterior)

Radial Error : 0.49598 mm

CyberKnife Overview

- **Tracking Methods:**
 - **6D Skull**
 - **Xsight Lung**
 - **Xsight Spine**
 - **Fiducial**
 - **Synchrony (Optical)**



CyberKnife Overview

- Measure total system accuracy:
 - Localization
 - Mechanical targeting
 - Planning Errors



CyberKnife Overview

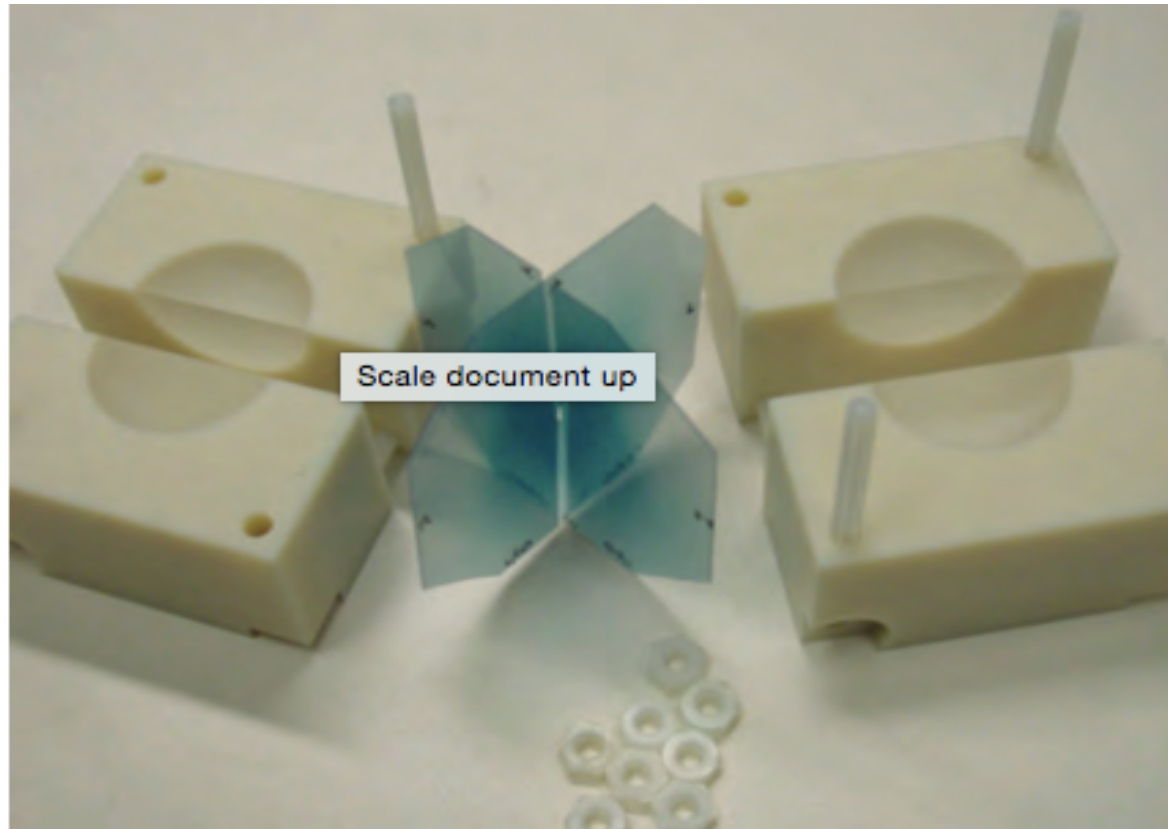
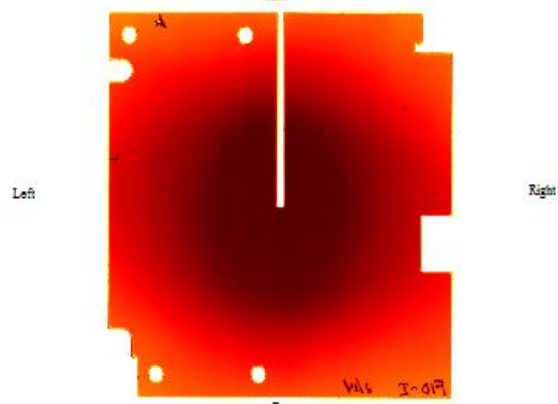


FIG. 9. The E2E ballcube used for fiducial and cranial tracking tests. A hidden target is irradiated. The orthogonal films are analyzed for spatial accuracy of dose delivery and can also be used for film dosimetry as plan verification. Figure courtesy of Accuray Inc.

Image 1

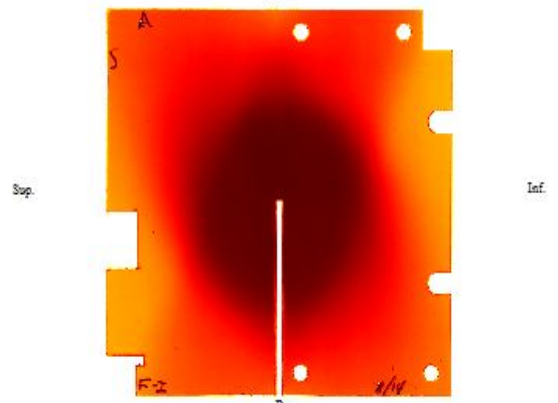
Ant.



Pos.

Image 2

Ant.



Pos.



End-to-End (E2E) Film Analysis

Image 1 Threshold Area



Image 1 Threshold Area Information	
Centroid Area:	169737
Pixels to Left:	373.06
Pixels to Top:	380.84
Eccentricity:	1.24

Image 2 Threshold Area

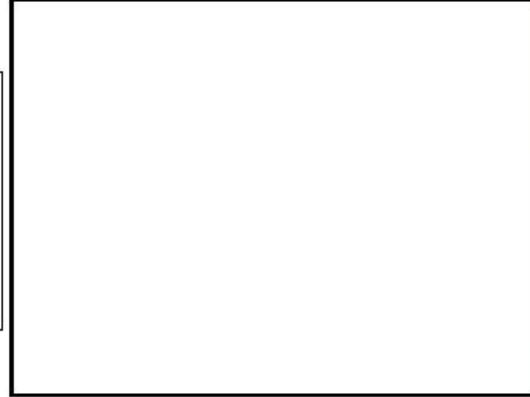


Image 2 Threshold Area Information	
Centroid Area:	136596
Pixels to Left:	379.96
Pixels to Top:	382.27
Eccentricity:	1.24

Image 1 Multiple Threshold Contours



Image 2 Multiple Threshold Contours



E2E Reference Information		Calibration Information	
Test:	xlt post	Hor pix/mm:	11.83
Date:	10/22	Vert pix/mm:	11.91
Film Label:		Sup. Pos mm:	31.75
Scanner:		Ant. Pos mm:	31.75
Film Type:		Left Pos mm:	31.75
Film Batch:			
Analysis Color Channel:	RED		
Image Bit Depth:	48		

Pixel Measurement Information		Contour Threshold: 24595	
Minimum:	18759	BG Film:	46278

Image 1 (A/L Image) Info	
mm from left edge:	31.53
mm from anterior edge:	31.98
contour area/ball area:	1.52

Image 2 (A/S Image) Info	
mm from superior edge:	32.12
mm from anterior edge:	32.1
contour area/ball area:	1.22

Error Information	
left error mm:	0.22
anterior error mm (A/L image):	-0.23
superior error mm:	-0.37
anterior error mm (A/S image):	-0.35
average anterior error mm:	-0.29
TOTAL TARGETING ERROR mm:	0.51

CyberKnife Overview

IV.B. Daily QA

Section	Item	Tolerance
II.A.2	Safety interlocks (Door, console EMO, Key)	Functional
	CCTV cameras and monitors	Functional
	Audio monitor	Functional
	Collimator assembly collision detector	Functional
II.B.1	Accelerator warm-up: 6000 MU for open chambers, 3000 MU for sealed chambers	N/A
	Accelerator output	<2%: no change needed >2%: adjust calibration
	Detection of incorrect and missing secondary collimator	Functional
III.B.2	Visual check of beam laser and a standard floor mark.	<1 mm
III.C.1	AQA test	< 1 mm from baseline

CyberKnife Overview

IV.C. Monthly QA

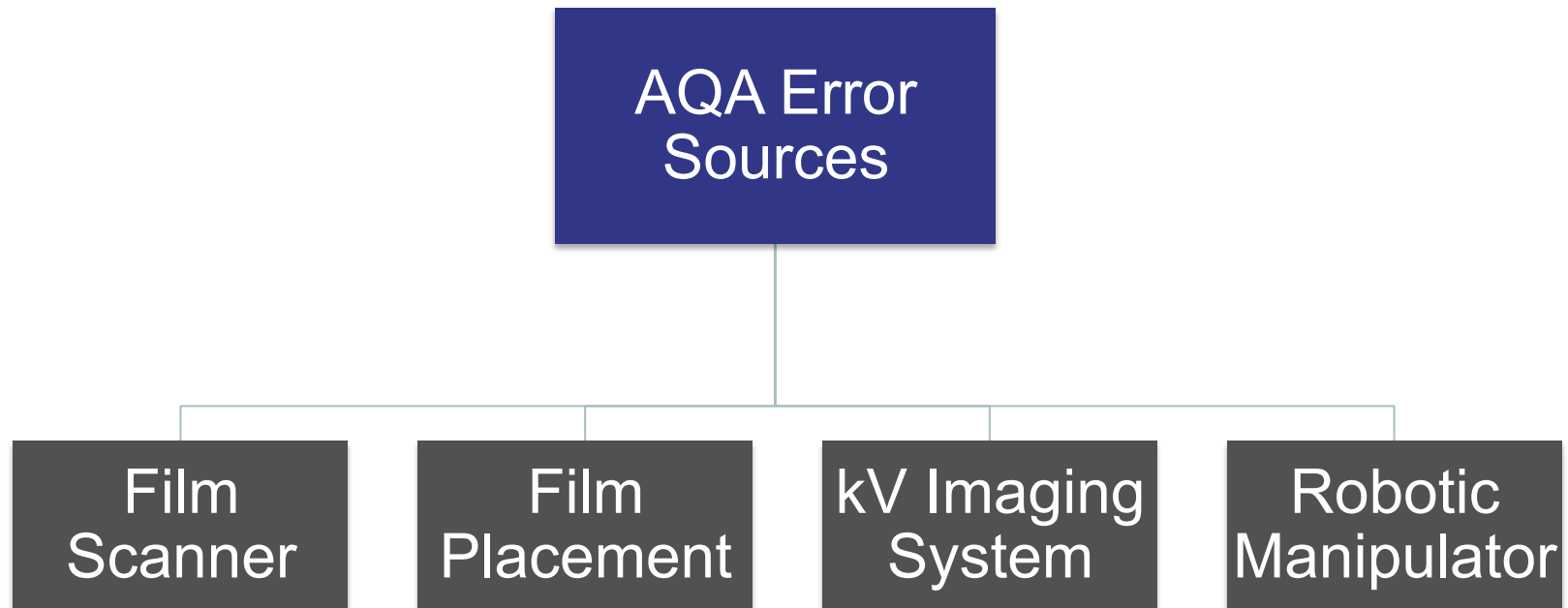
Section	Item	Tolerance
II.A.2	Safety interlocks.	Functional
II.B.2	Energy constancy.	2%
	Beam symmetry.	>3%
	Beam shape.	>2% Compared to beam data
	Output.	> 2%
II.C.1	Imager alignment.	1 mm or center pixel \pm 2 pixels
II.C.3	Contrast, noise, and spatial resolution of amorphous silicon detector.	To be decided by user based on available literature
	Homogeneity/bad pixels.	
II.D	Custom CT model: CT QA (spatial accuracy, electron density).	See TG 66 (Ref. 29)
III.B.1	Verify relative location of beam laser vs. radiation CAX has not changed.	0.5 mm
III.B.2	Visually check isocentric plan to verify beam laser illuminates isocrystal; rotate through path sets each month	Laser on isocrystal for each node
III.C.2	Intracranial and extracranial E2E; set schedule to cycle through each clinically used tracking method and path.	<0.95 mm or <1.5 mm for motion tracking
III.C.3	Nonisocentric patient QA or DQA; ideally performed quarterly.	DTA 2 mm/2%; Synchrony DTA 3%/3 mm
III.D	Observe Synchrony treatment or simulation; listen for unusual noise and visually check for vibrations.	No significant change

CyberKnife Overview

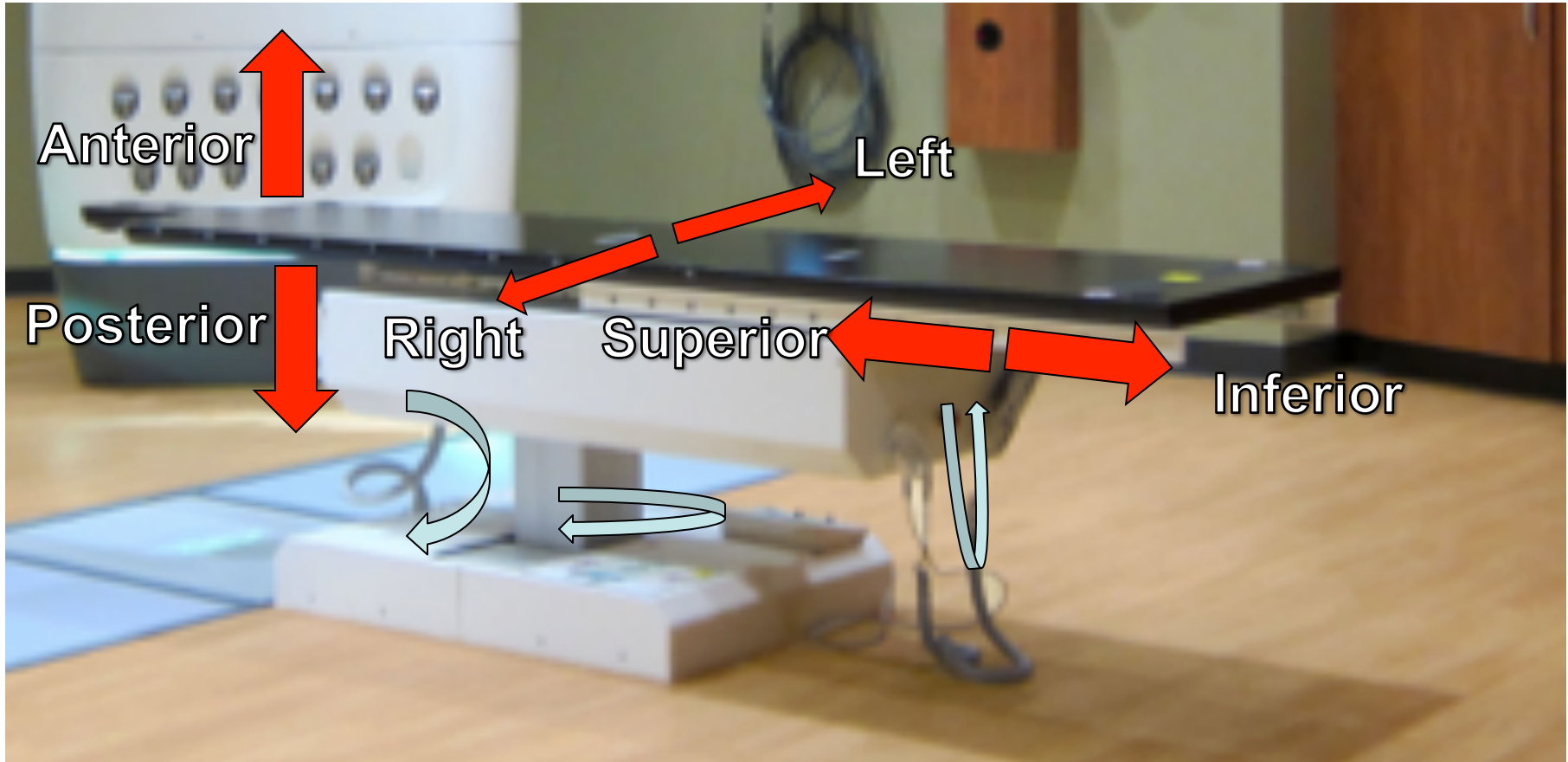
IV.D. Annual QA

Section	Item	Tolerance
II.A.2	EPO button	Functional
II.B.3	TG 51 or IAEA TRS-398, including secondary independent check. Beam data checks on at least three collimators, including largest and smallest collimator (TPR or PDD, OCR, output factors). Dose output linearity to lowest MU/beam used.	Adjust calibration if >1% difference is found To be decided by user 1%
II.C.2	Imager kVp accuracy, mA station exposure linearity, exposure reproducibility, focal spot size.	See Table 1 for references
II.C.3	Signal to noise ratio, contrast-to-noise ratio, relative modulation transfer function, imager sensitivity stability, bad pixel count and pattern, uniformity corrected images, detector centering, and imager gain statistics.	Compare to baseline
II.D	TG 53 as applicable. CT QA (in addition to monthly). Data security and verification.	TG 53 (Ref. 26) See TG 66 (Ref. 29) Functional
III.B.2	2nd Order Path Calibration; currently only possible with the help of a service engineer.	Each node < 0.5 mm RMS < 0.3 mm
III.D	Check noise level of optical markers.	<0.2 mm
IV.C	Run Synchrony E2E test with at least 20 deg phase shift; analyze penumbra spread.	To be decided by user
IV.C	Monthly QA.	In addition to tolerances listed above, update all parameters and checklists
IV.B	Daily QA.	Update parameters

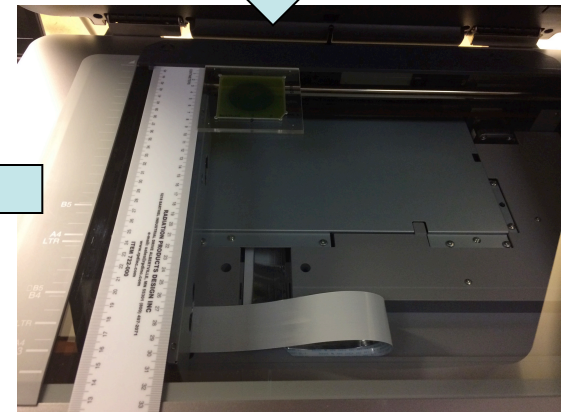
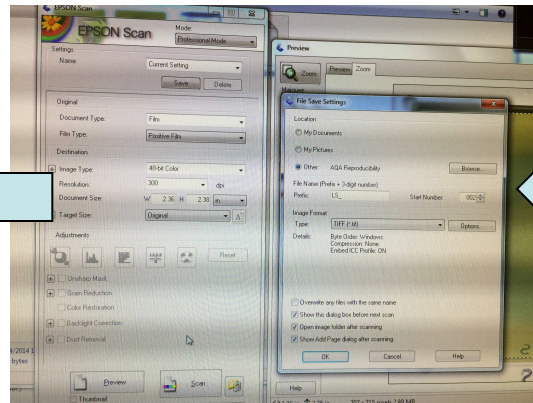
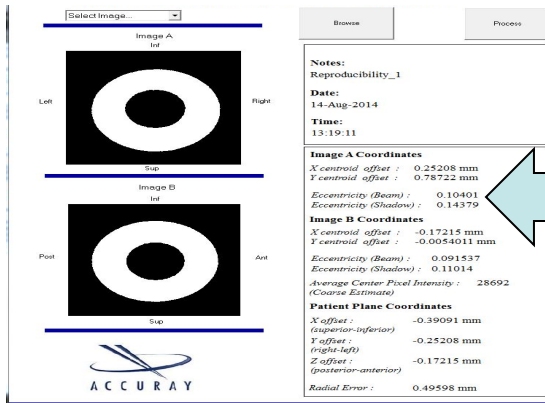
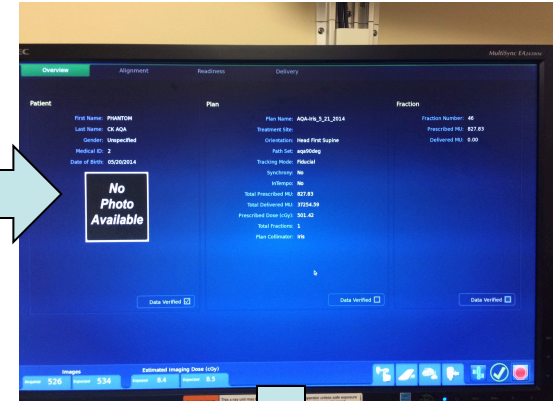
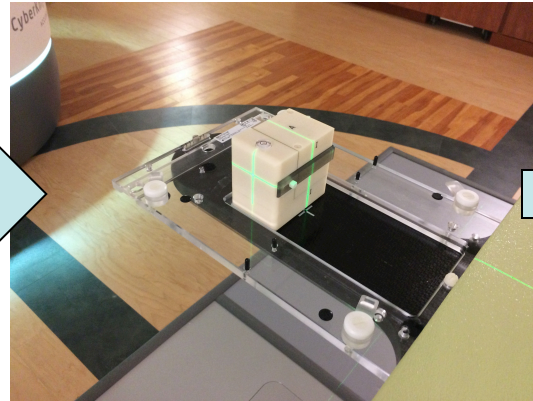
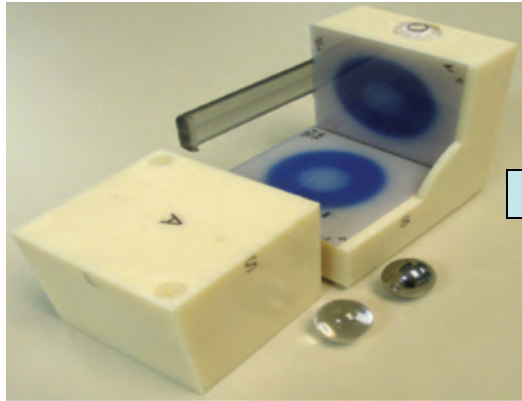
Methods: CyberKnife AQA Overview



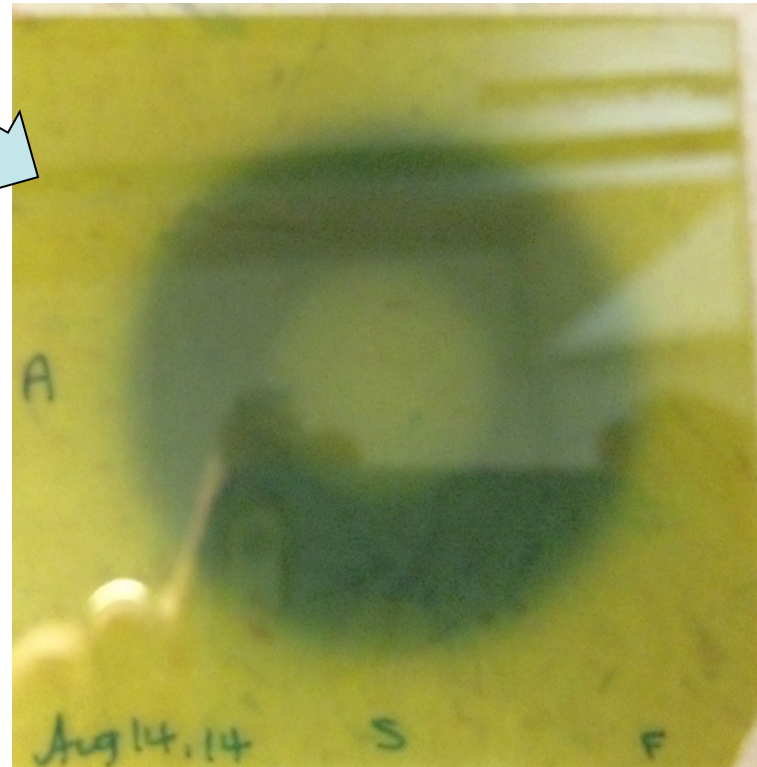
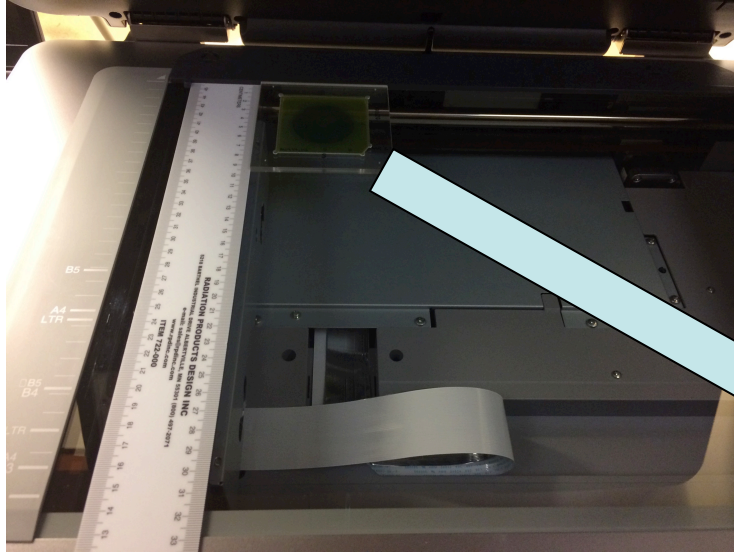
CyberKnife AQA



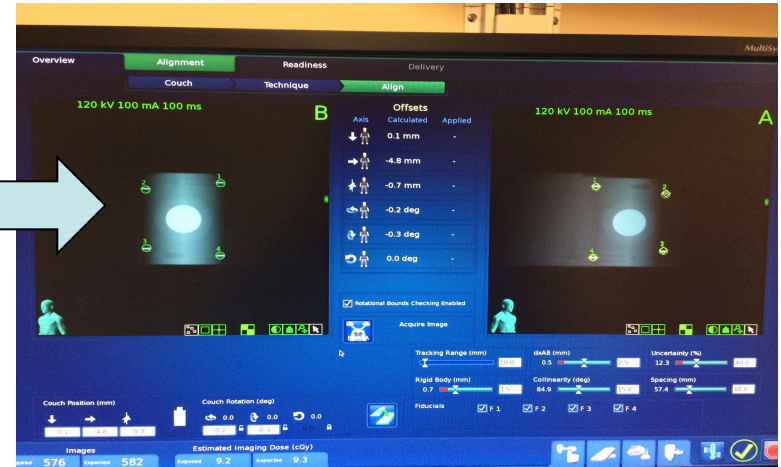
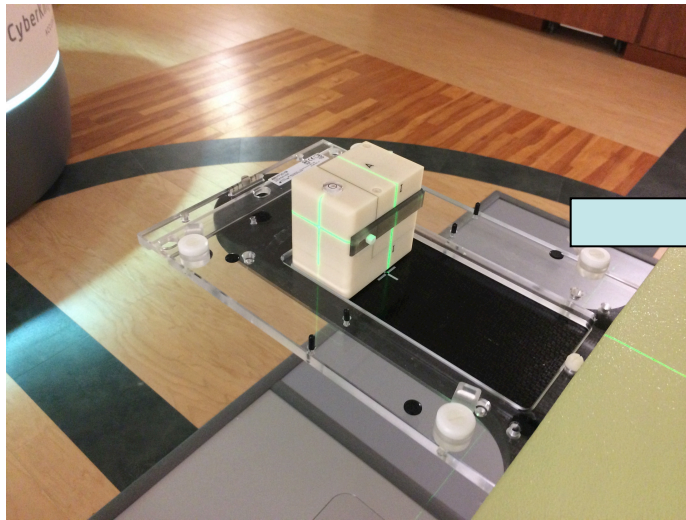
Methods: Film Scanner



Methods: Film Placement



Methods: kV Imaging System



Methods: Robotic Manipulator

KUKA

KUKA Robotics



Robots



Controllers



Software



Applications



Service

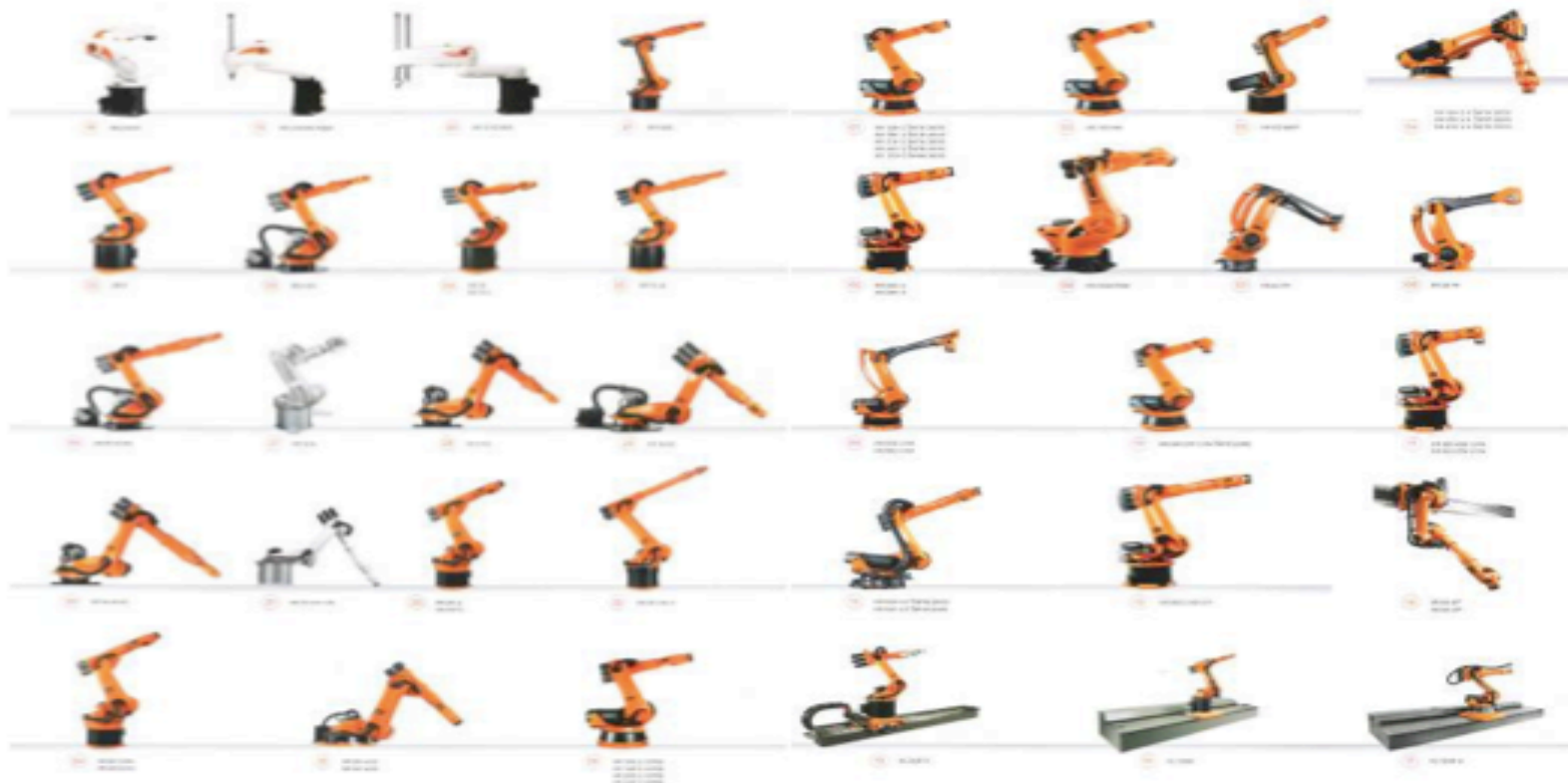


Platforms

Methods: Robotic Manipulator

KUKA

KUKA Robotics – Product range



Methods: Robotic Manipulator

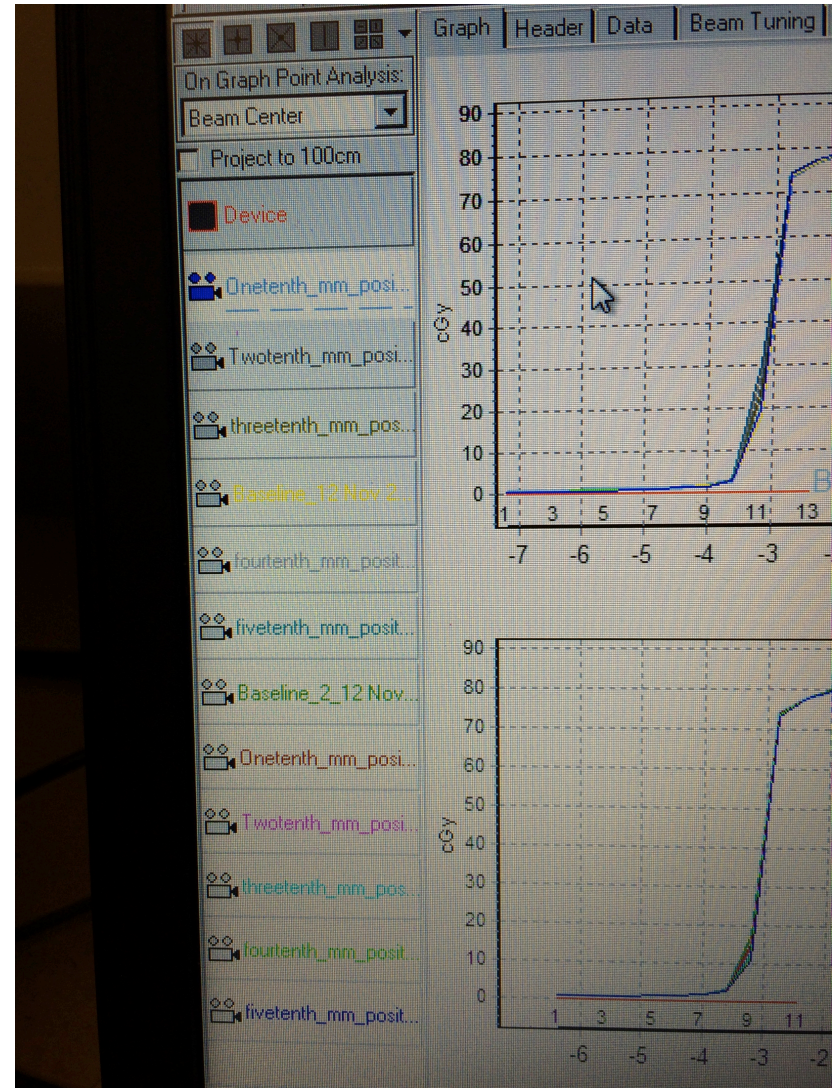
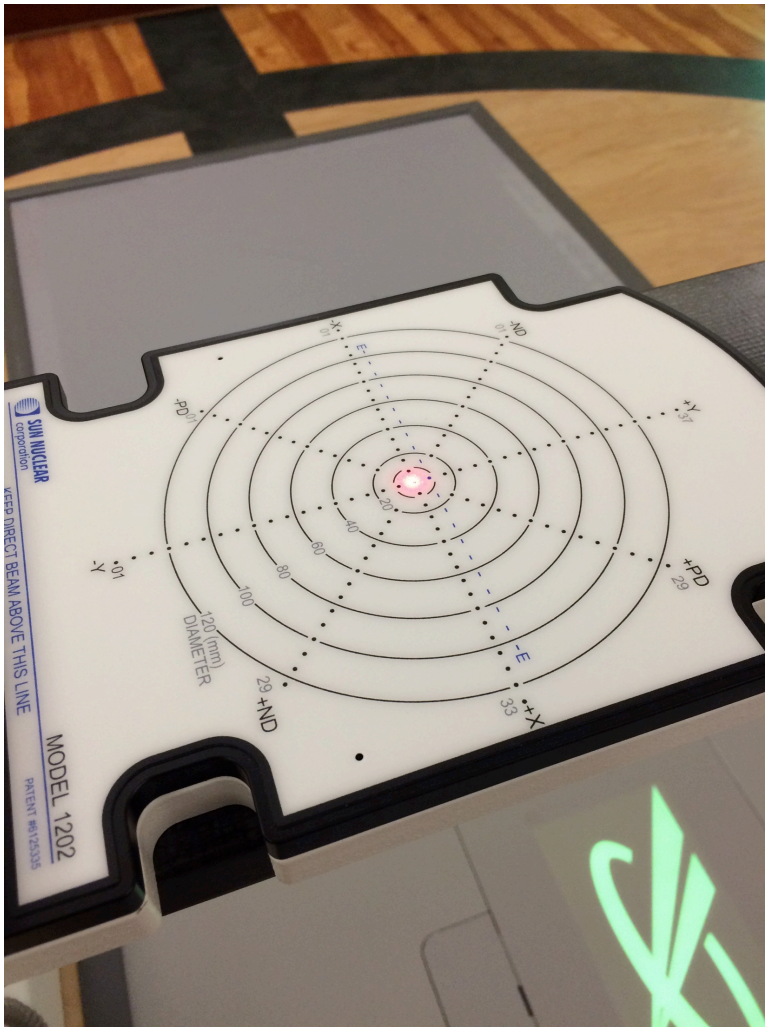
KUKA

KUKA Medical Robots – Accuray Cyberknife



- Sub-millimeter accuracy requirements of full body radiosurgery
- System offers unprecedented accessibility to tumors anywhere in the body
- The KUKA robot guides a linac to treat tumours with X-Ray beam. The linac can be positioned highly flexible by the robot.
- Respiratory guided robot movements guaranties lower dose application.

Methods: Robotic Manipulator



Results: Film Scanner - IRIS

LS -- Image A						
No.	File Name	X- Centroid Offset (mm)	Y-Centroid Offset (mm)	Eccentricity (Beam)	Eccentricity (Shadow)	
1	LS_001	0.15224	0.05697	0.094898	0.09108	
2	LS_002	0.15989	0.06253	0.092244	0.10207	
3	LS_003	0.16041	0.06330	0.091842	0.10605	
4	LS_004	0.13842	0.07718	0.094171	0.08755	
5	LS_005	0.16467	0.05009	0.091589	0.09529	
6	LS_006	0.15039	0.06925	0.089576	0.09618	
7	LS_007	0.13913	0.06514	0.091133	0.10940	
8	LS_008	0.16647	0.05238	0.094748	0.05274	
9	LS_009	0.15355	0.07133	0.093351	0.08664	
10	LS_010	0.14791	0.07004	0.097707	0.11160	
Average (mm)		0.15331	0.06382	0.093126	0.09386	
Std. Dev (mm)		0.00976	0.00865	0.00234	0.01690	
Std. Dev of Mean		0.00309	0.00273	0.00074	0.00534	

AS -- Image B						
No.	File Name	X- Centroid Offset (mm)	Y-Centroid Offset (mm)	Eccentricity (Beam)	Eccentricity (Shadow)	
1	AS_001	0.11747	0.16183	0.117470	0.16813	
2	AS_002	0.11778	0.17677	0.110630	0.10294	
3	AS_003	0.09106	0.15471	0.110020	0.11302	
4	AS_004	0.09936	0.14129	0.112460	0.09207	
5	AS_005	0.12803	0.17102	0.114650	0.09876	
6	AS_006	0.09610	0.14853	0.116020	0.10221	
7	AS_007	0.13658	0.16013	0.113610	0.10065	
8	AS_008	0.10186	0.13369	0.112030	0.10312	
9	AS_009	0.09315	0.15132	0.108080	0.13331	
10	AS_010	0.10008	0.14522	0.111700	0.11524	
Average (mm)		0.10815	0.15445	0.112667	0.11295	
Std. Dev (mm)		0.01573	0.01331	0.00284	0.02252	
Std. Dev of Mean		0.00497	0.00421	0.00090	0.00712	

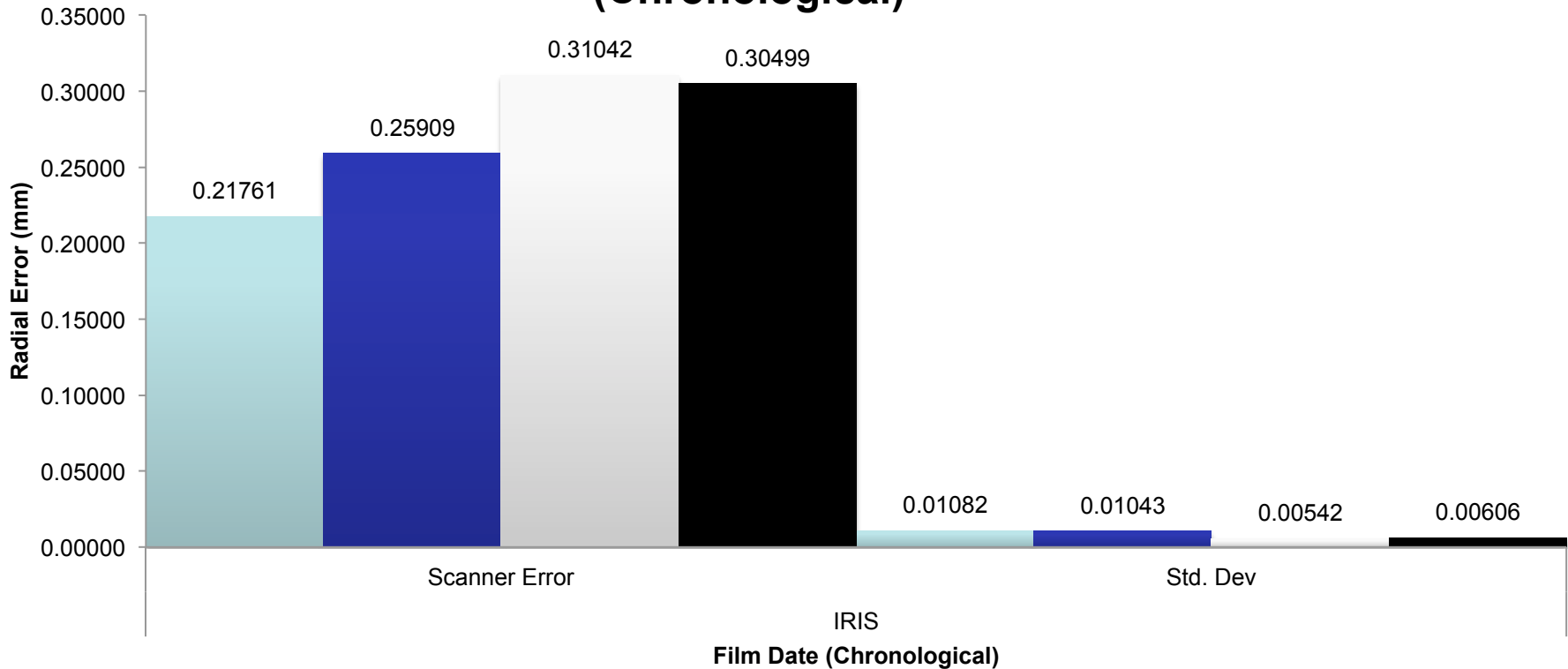
Results: Film Scanner - IRIS

Patient Plane Coordinates				
X-Offset (superior-inferior)(mm)	Y-Offset (right-left) (mm)	Z-Offset (posterior-anterior)	Radial Error (mm)	
-0.10940	-0.15224	0.11747	0.22124	
-0.11965	-0.15989	0.11778	0.23184	
-0.10901	-0.16041	0.09106	0.21425	
-0.10924	-0.13842	0.09936	0.20240	
-0.11056	-0.16467	0.12803	0.23608	
-0.10889	-0.15039	0.09610	0.20907	
-0.11263	-0.13913	0.13658	0.22516	
-0.09304	-0.16647	0.10186	0.21620	
-0.11132	-0.15355	0.09315	0.21130	
-0.10763	-0.14791	0.10080	0.20851	
-0.10914	-0.15331	0.10822	0.21761	
0.00659	0.00976	0.01569	0.01082	
0.00208	0.00309	0.00496	0.00342	
			Average (mm)	
			Std. Dev (mm)	
			Std. Dev of Mean	

$$\text{Radial Error} = \sqrt{\text{Offset}_{\text{Inferior}}^{\text{Superior}^2} + \text{Offset}_{\text{Left}}^{\text{Right}^2} + \text{Offset}_{\text{Posterior}}^{\text{Anterior}^2}}$$

Results: Film Scanner - IRIS

AQA IRIS 35mm: Radial Error (mm) vs. Film Date (Chronological)



Results: Film Scanner - FIXED

LS -- Image A					
No.	File Name	X- Centroid Offset (mm)	Y-Centroid Offset (mm)	Eccentricity (Beam)	Eccentricity (Shadow)
1	LS_001	0.15049	0.07353	0.898740	0.10617
2	LS_002	0.15049	0.06319	0.092200	0.10746
3	LS_003	0.15552	0.05539	0.094058	0.10344
4	LS_004	0.16502	0.06728	0.094284	0.12099
5	LS_005	0.15220	0.05473	0.093583	0.08871
6	LS_006	0.14153	0.06585	0.096995	0.10927
7	LS_007	0.15224	0.05859	0.094746	0.09912
8	LS_008	0.15367	0.06584	0.094032	0.10983
9	LS_009	0.13647	0.06226	0.092131	0.08872
10	LS_010	0.16956	0.06136	0.094127	0.06008
Average (mm)		0.15272	0.06280	0.174490	0.09938
Std. Dev (mm)		0.00968	0.00572	0.25448	0.01691
Std. Dev of Mean		0.00306	0.00181	0.08047	0.00535

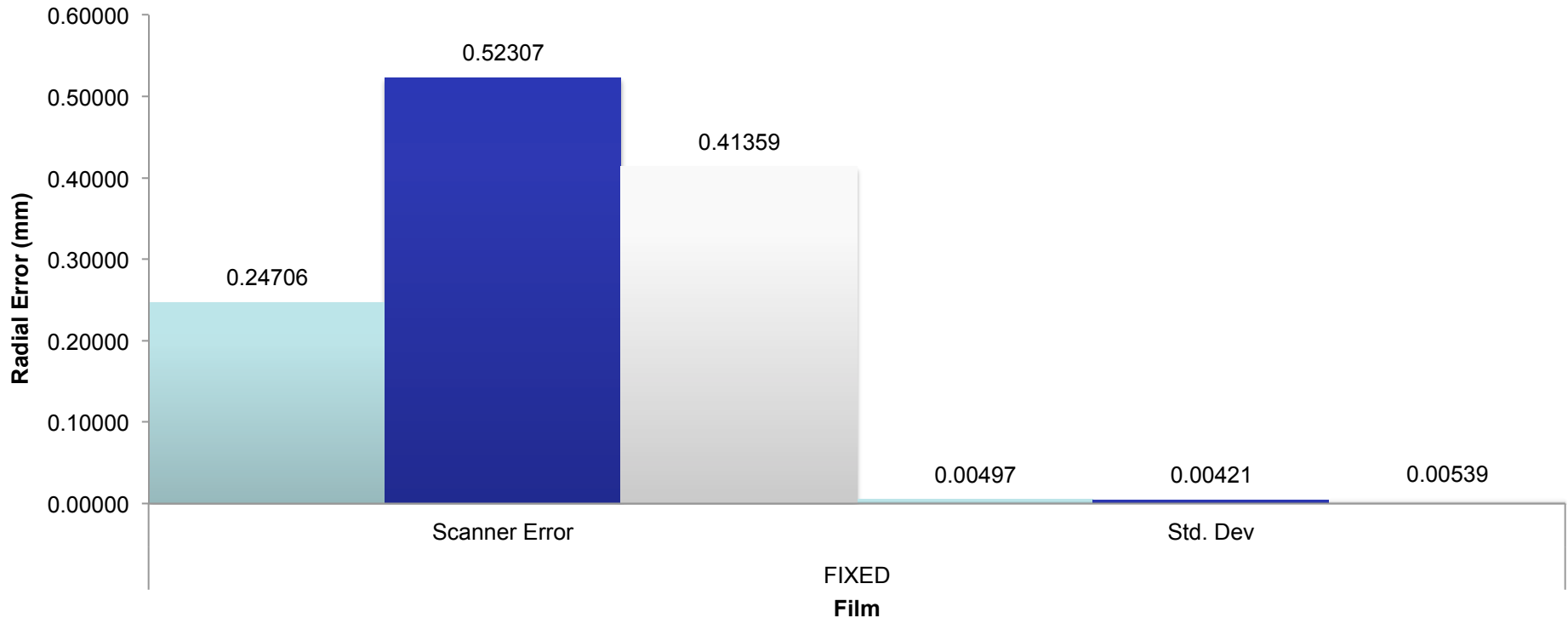
AS -- Image B					
No.	File Name	X- Centroid Offset (mm)	Y-Centroid Offset (mm)	Eccentricity (Beam)	Eccentricity (Shadow)
1	AS_001	0.13626	0.15850	0.107890	0.08122
2	AS_002	0.14104	0.15867	0.109800	0.12373
3	AS_003	0.13119	0.16677	0.110670	0.10403
4	AS_004	0.13533	0.15267	0.113290	0.10077
5	AS_005	0.14163	0.16231	0.108950	0.12673
6	AS_006	0.08332	0.18620	0.110590	0.11475
7	AS_007	0.09402	0.13654	0.110880	0.11136
8	AS_008	0.13419	0.16511	0.109230	0.09897
9	AS_009	0.13149	0.14722	0.113120	0.10121
10	AS_010	0.13776	0.15506	0.112440	0.10511
Average (mm)		0.12662	0.15891	0.110686	0.10679
Std. Dev (mm)		0.02046	0.01311	0.00181	0.01317
Std. Dev of Mean		0.00647	0.00415	0.00057	0.00417

Results: Film Scanner - FIXED

Patient Plane Coordinates				
X-Offset (superior-inferior)(mm)	Y-Offset (right-left) (mm)	Z-Offset (posterior-anterior) (mm)	Radial Error (mm)	
-0.11602	-0.15049	0.13626	0.23382	
-0.11093	-0.15049	0.14104	0.23419	
-0.11108	-0.15552	0.13119	0.23181	
-0.11002	-0.16502	0.13533	0.24011	
-0.10852	-0.15220	0.14163	0.23452	
-0.10724	-0.14153	0.08332	0.19614	
-0.09756	-0.15224	0.09402	0.20380	
-0.11548	-0.15637	0.13419	0.23621	
-0.10474	-0.13647	0.13129	0.21641	
-0.10821	-0.16956	0.13776	0.24380	
-0.10898	-0.15299	0.12660	0.22708	Average (mm)
0.00530	0.00975	0.02045	0.01605	Std. Dev (mm)
0.00168	0.00308	0.00647	0.00508	Std. Dev of Mean

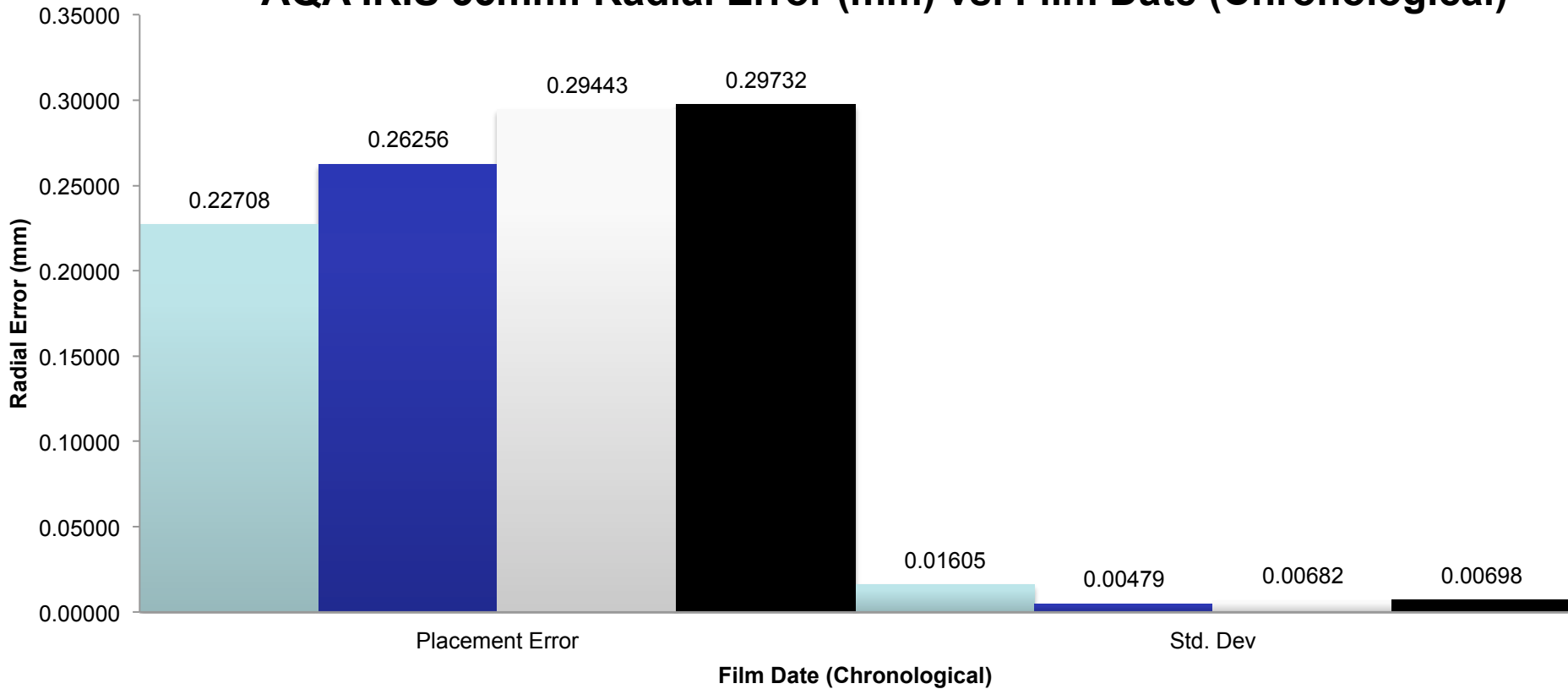
Results: Film Scanner - FIXED

AQA Fixed 35mm: Radial Error (mm) vs. Film Date (Chronological)



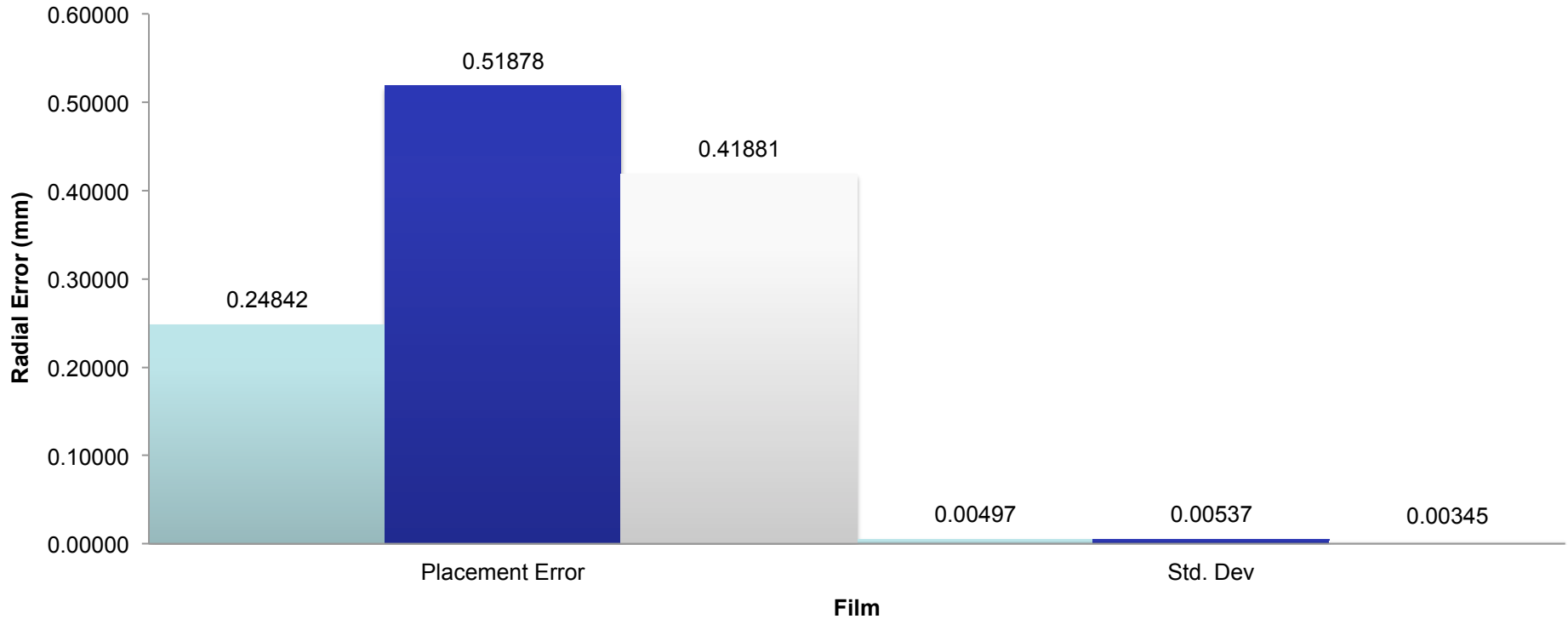
Results: Film Placement - IRIS

AQA IRIS 35mm: Radial Error (mm) vs. Film Date (Chronological)



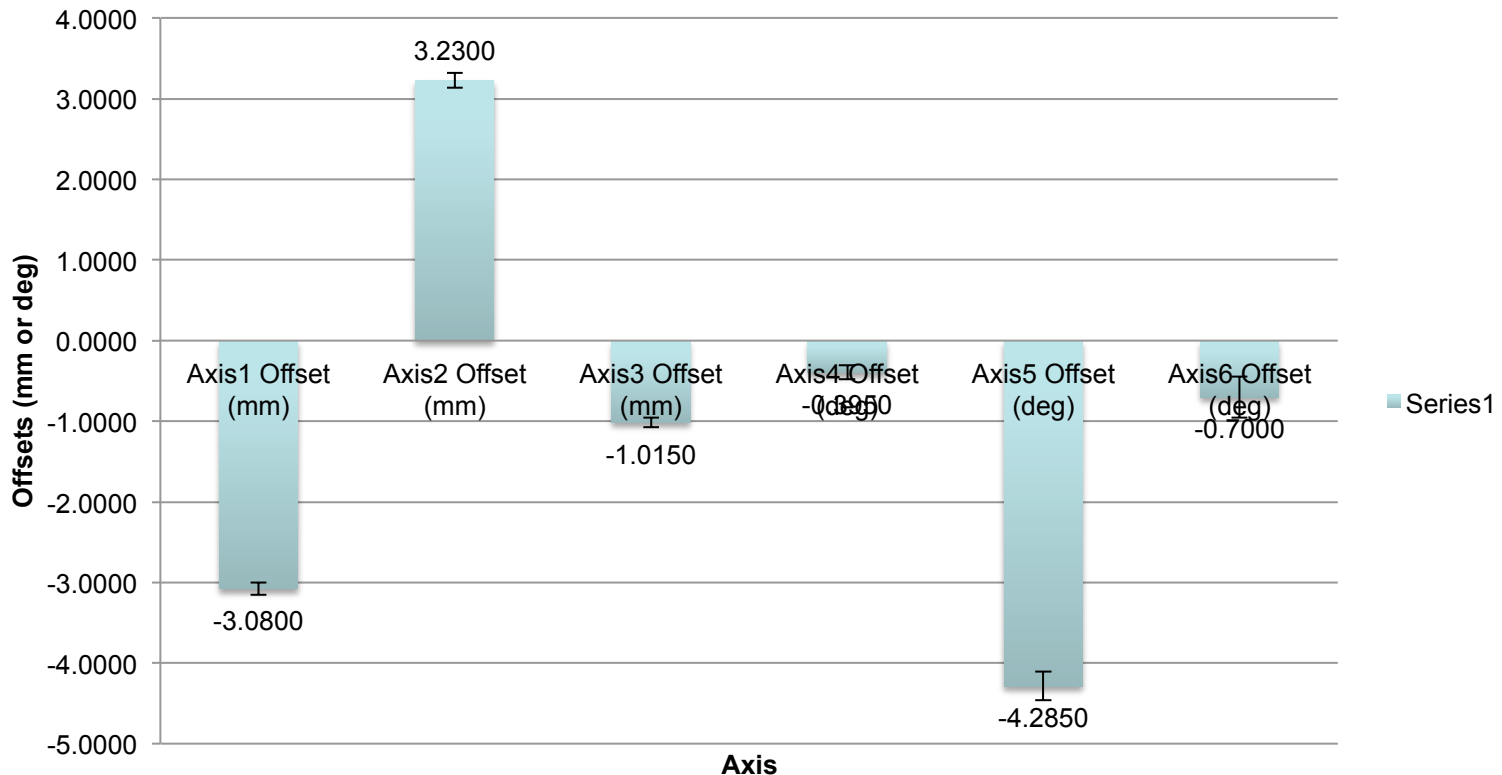
Results: Film Placement - FIXED

AQA Fixed 35mm: Radial Error (mm) vs. Film Date (Chronological)



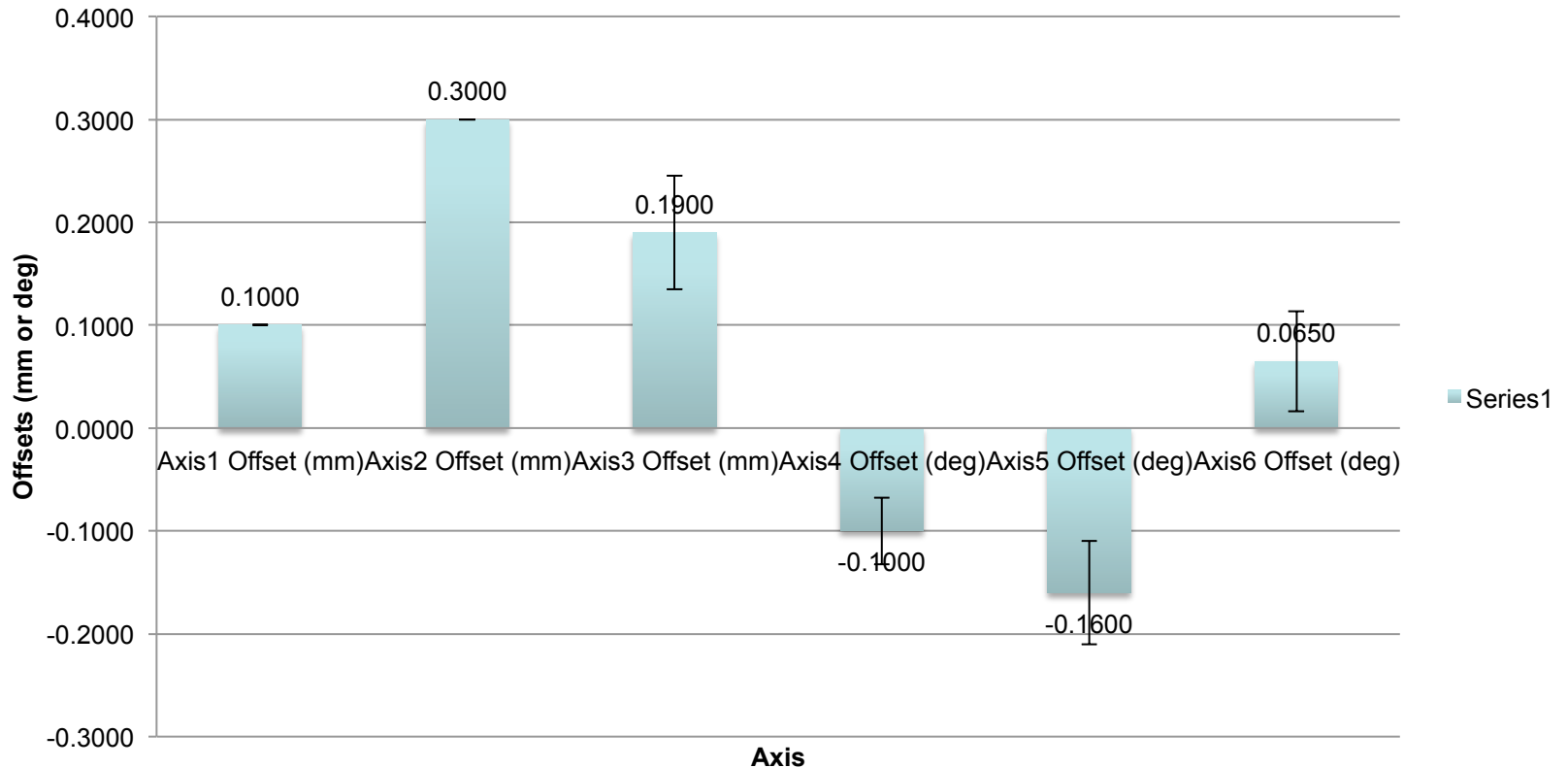
Results: kV Imaging – 6D Skull

kV X-ray Imaging System Repeatability: Offsets (mm or deg) vs. Axis



Results: kV Imaging - Fiducial

kV X-ray Imaging System Repeatability: Offsets (mm or deg) vs. Axis



Results: kV Imaging System

Tracking Algorithm: Fiducial Deviations

	Axis1 (mm)	Axis2 (mm)	Axis3 (mm)	Axis4 (deg)	Axis5 (deg)	Axis6 (deg)
1	0.0503	0.0224	0.0999	0.1701	0.0000	0.0224
2	0.0000	0.0000	0.0000	0.0000	0.0503	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0452	0.0452	0.0452	0.0452
5	0.0489	0.0000	0.0821	0.0366	0.0470	0.1196
6	0.0000	0.0000	0.0553	0.0324	0.0503	0.0489

Tracking Algorithm: 6D Skull Deviations

	Axis1 (mm)	Axis2 (mm)	Axis3 (mm)	Axis4 (deg)	Axis5 (deg)	Axis6 (deg)
1	0.0768	0.0923	0.0587	0.0887	0.1755	0.2575
2	0.0000	0.0523	0.0598	0.0366	0.0605	0.0999
3	0.0510	0.0686	0.0510	0.0444	0.0000	0.0000

Results: Robotic Manipulator

Baseline Measurement -- SRS Pre-programmed position

No.	X (cm)	Y (cm)	Positive Diagonal (cm)	Negative Diagonal (cm)
<i>Baseline1</i>	-0.05	0.02	-0.03	-0.05
<i>Baseline2</i>	-0.05	0.02	-0.03	-0.05
<i>Baseline3</i>	-0.05	0.02	-0.03	-0.05
<i>Baseline4</i>	-0.05	0.02	-0.03	-0.05
<i>Baseline5</i>	-0.05	0.02	-0.03	-0.05
<i>Baseline Average</i>	-0.05	0.02	-0.03	-0.05
<i>Baseline Std Dev</i>	0	0	0	0
<i>Baseline Std Error</i>	0	0	0	0

Results: Robotic Manipulator

CyberKnife M6 -- Robot Localization Repeatability

No.	X (cm)	Y (cm)	Positive Diagonal (cm)	Negative Diagonal (cm)
1	-0.05	0.02	-0.03	-0.05
2	-0.05	0.02	-0.03	-0.05
3	-0.05	0.02	-0.03	-0.05
4	-0.05	0.02	-0.03	-0.05
5	-0.05	0.02	-0.03	-0.05
6	-0.05	0.02	-0.03	-0.05
7	-0.05	0.02	-0.03	-0.05
8	-0.05	0.02	-0.03	-0.05
9	-0.05	0.02	-0.03	-0.05
10	-0.05	0.02	-0.03	-0.05
Average (cm)	-0.05	0.02	-0.03	-0.05
Std. Dev (cm)	0.00	0.00	0.00	0.00
Std. error	0.00	0.00	0.00	0.00

Results: Summary

CyberKnife M6 Treatment Delivery Uncertainties - IRIS

<i>Uncertainty Source</i>	<i>Uncertainty, mm, +/- 3SD</i>
Flat Bed Film Scanner	0.025
Film Placement	0.001
kV Imaging System Fiducial Tracking	0.150
Robot Mechanical*	0.173
Total Uncertainty, mm, +/-3SD	0.349

CyberKnife M6 Treatment Delivery Uncertainties - FIXED

<i>Uncertainty Source</i>	<i>Uncertainty, mm, +/- 3SD</i>
Flat Bed Film Scanner	0.015
Film Placement	0.001
kV Imaging System Fiducial Tracking	0.150
Robot Mechanical*	0.173
Total Uncertainty, mm, +/-3SD	0.339

Conclusions

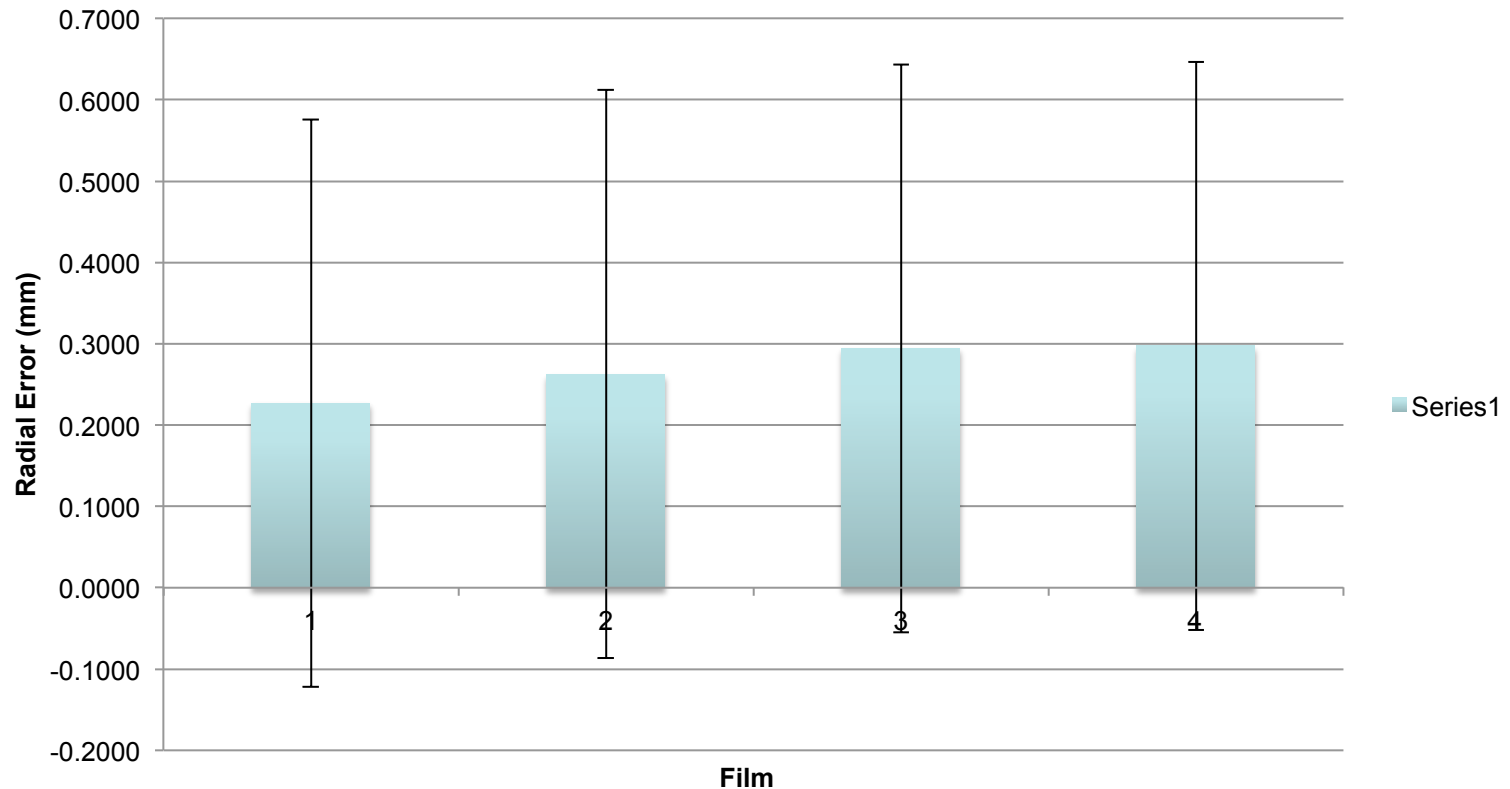
The total AQA uncertainty appears to be largely due to the kV imaging system. These results suggest an uncertainty of less than 0.1 mm for the film, film scanner, and robot components of the AQA test. The kV imaging system uncertainty could reach 0.3 mm and is the main source of uncertainty. This information explains greatest weakness in daily CyberKnife QA and may be useful in establishing realistic expectations of daily AQA results.

Conclusions

IRIS*			
Average (mm)	System Error IRIS, mm, +/- 3SD	Tolerance StackUp	
		-	+
0.2271	0.3493	-0.1222	0.5764
0.2626	0.3493	-0.0867	0.6118
0.2944	0.3493	-0.0548	0.6437
0.2973	0.3493	-0.0519	0.6466

Conclusions

Film Radial Error & AQA Error Tolerances - IRIS

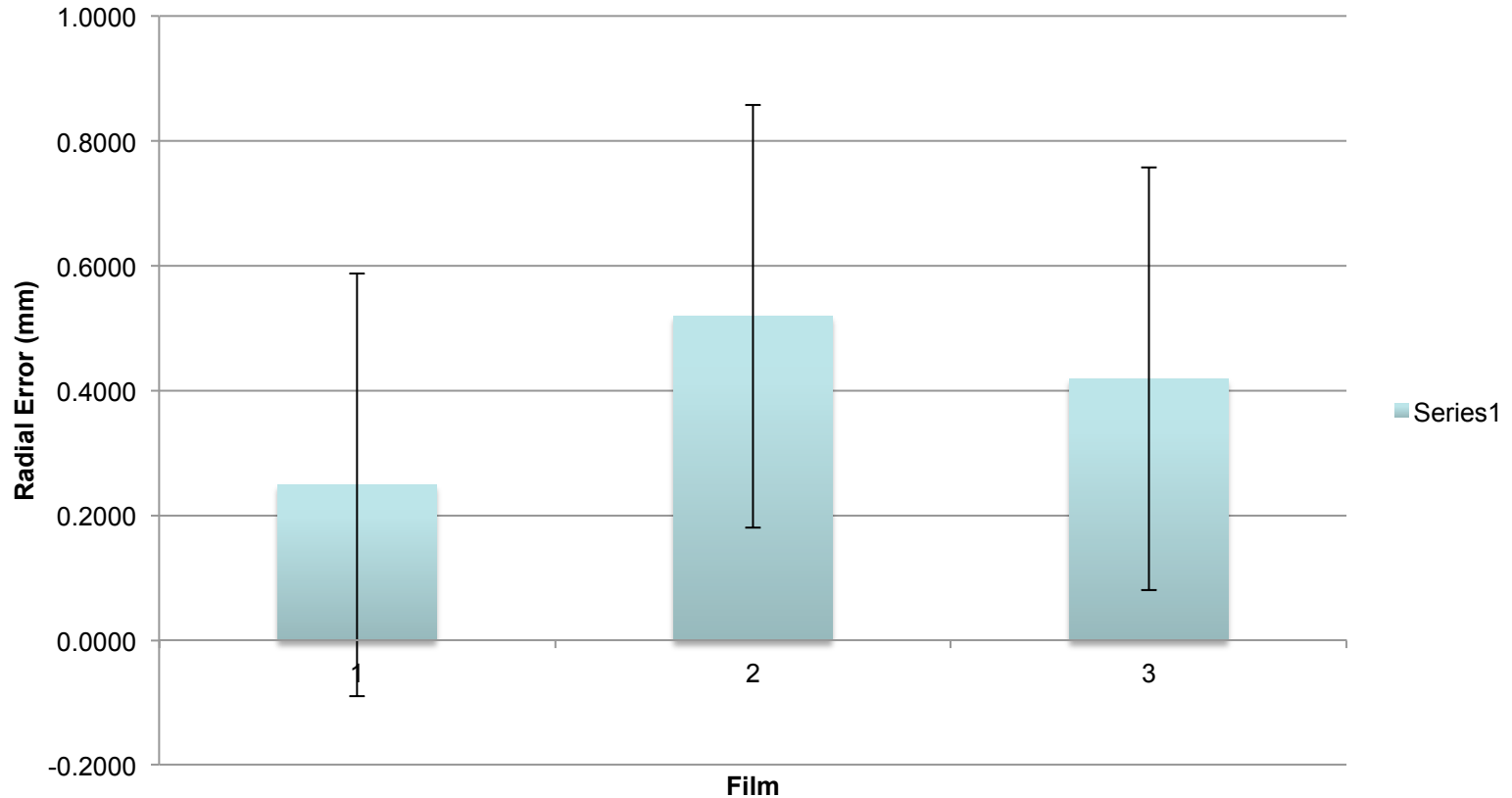


Conclusions

FIXED*				
Average (mm)	System Error FIXED, mm, +/- 3SD	Tolerance StackUp		
		-	+	
0.2484	0.3387	-0.0902	0.5871	
0.5188	0.3387	0.1801	0.8574	
0.4188	0.3387	0.0802	0.7575	

Conclusions

Film Radial Error & AQA Error Tolerances - FIXED



Future Interests

1. Comparison of Tracking Algorithms

2. IRIS vs FIXED; AQA & E2E

3. SRS Profiler & Film for AQA

Procedures for Radial Error $>0.6\text{mm}$

- 1. Take repeat scans on scanner**
- 2. Place Film Again, repeat scan**
- 3. Verify Tracking Algorithm**
- 4. Repeat AQA**
- 5. Use SRS Profiler for repeat movements**
- 6. Call Accuray (delta Manip or other...)**

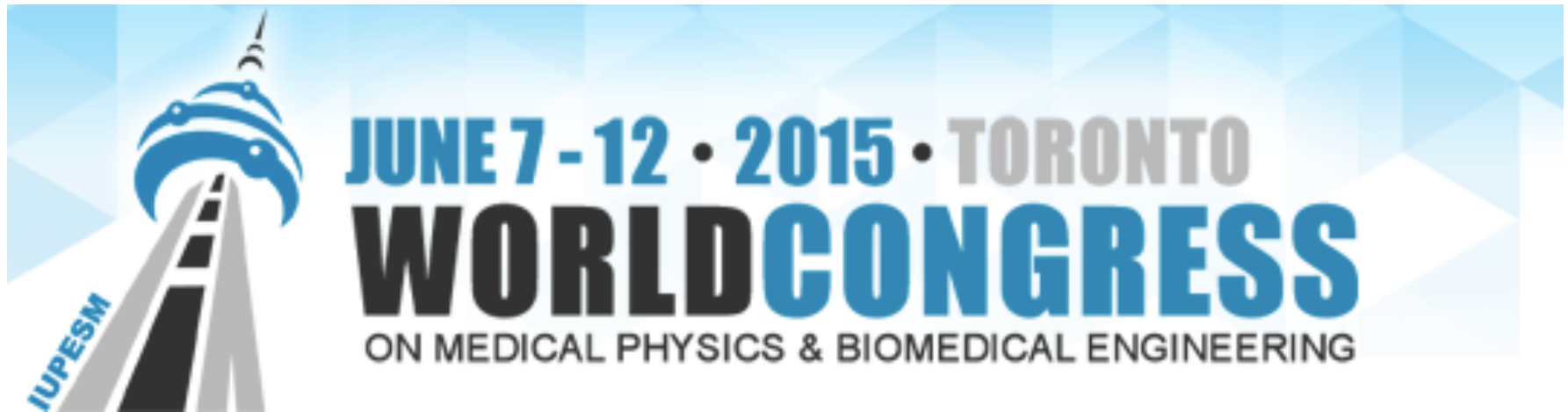
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Conference Acceptance



Abstract ID: 2433
Programm Nr: 2433
Type: Poster
Topic: TRACK 04: RADIATION ONCOLOGY / 11. Quality Assurance of the Planning & Treatment Delivery Process
Title: A Systematic Analysis Of The Error Sources Within The CyberKnife M6 Daily AQA Test
Authors: K.T. Jordan, A. Mayville, T. Bichay; Lacks Cancer Center -- Radiation Oncology, Mercy Health Grand Rapids, Grand Rapids/United States of America
Jury decision: **Accepted**

Thank You!

- Questions?