CyberKnife Technology in Ablative Radiation Therapy

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Objectives

- Components and work flow of CyberKnife
- Motion management of CyberKnife
- Dosimetry characteristics of CyberKnife
- New development of CyberKnife
- QA of CyberKnife

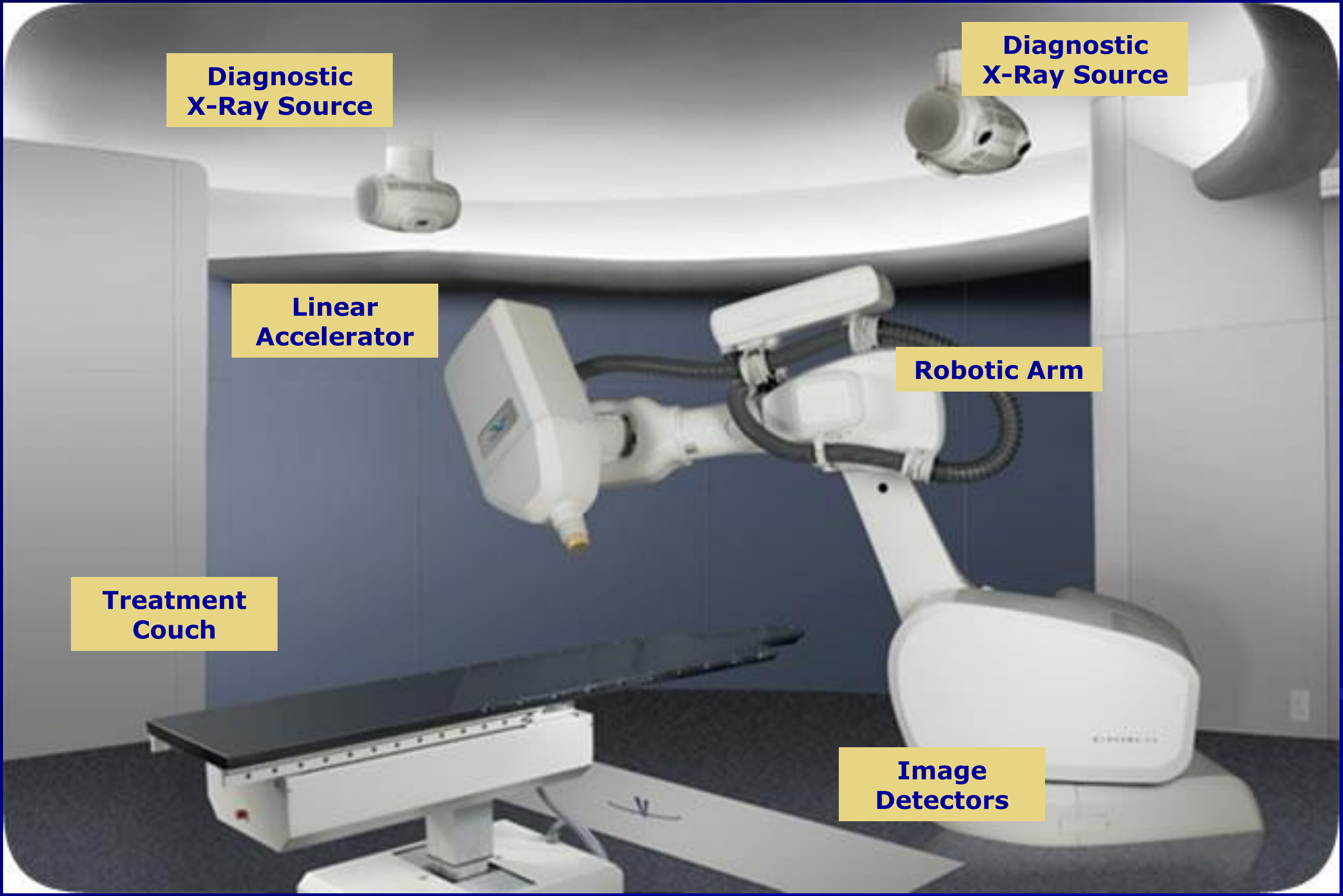
CyberKnife Components & treatment

Motion management

Dosimetry

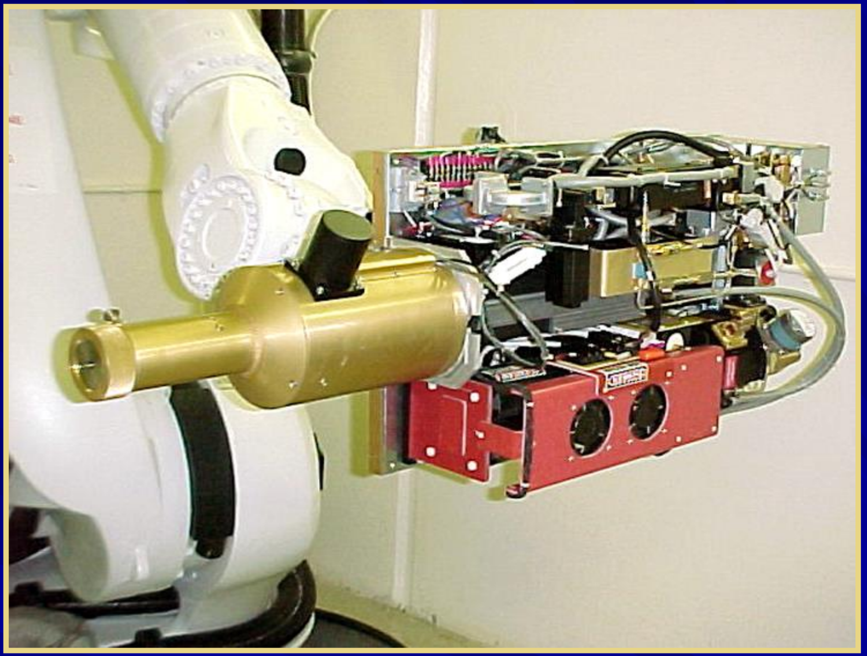
Quality Assurance

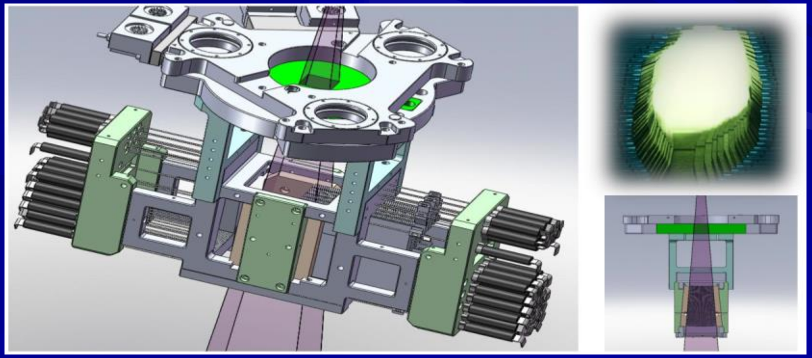
CyberKnife® Components



Linear Accelerator

- 330 lbs.
- 6 MV X-ray
- 1000 MU/min
- Three set collimators
  - 5 – 60 mm circular collimators
  - 5 – 60 mm dodecagonal (12-sided) IRIS variable aperture collimators
  - 100 x 120 mm MLC





Robot Specifications

Made by KUKA of Germany

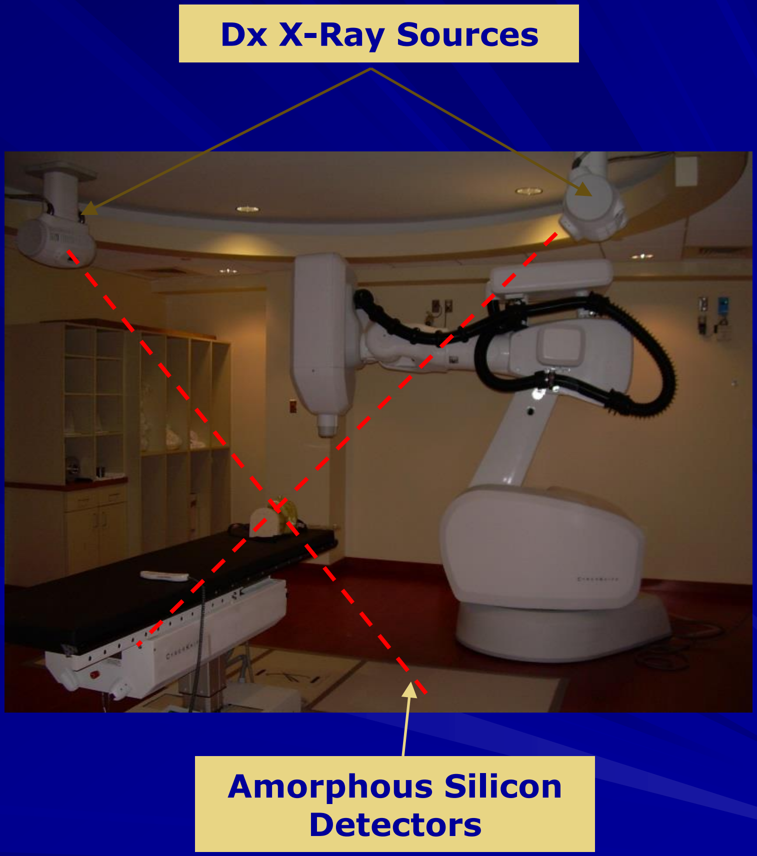
- ***6 axis / joint motion***
- 1,525 kg (w/Linac)
- 210 kg payload
- 208 VAC, 3 Phase (PDU)
- 0-45 ºC operating range
- <75% Relative humidity
- ***13 ft x 16 ft operating envelope (3 m reach)***
- ***0.12 mm repeatability***

5° Treatment Couch (Axum)

- Accommodates up to 159 kg patient (350 lbs)
- Motorized control with 5 degrees of freedom
  - Inferior-superior
  - Anterior-posterior
  - Right - left
  - Roll
  - Pitch

Image Tracking System

- 2 diagnostic X-Ray sources + 2 ASi image detectors (cameras)
- Patient imaged at 45° orthogonal angles
- Real-time, live images compared against DRRs generated from CT
- During treatment, Robot adjusts position based on the comparison

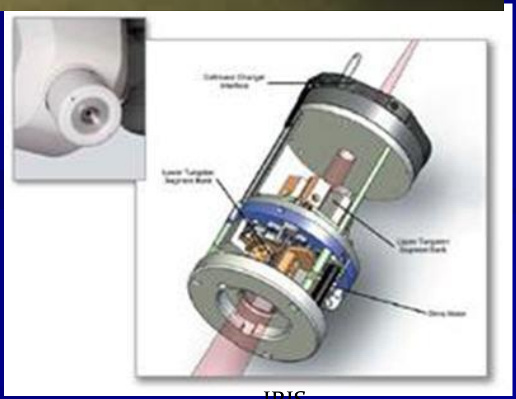


Development of CyberKnife

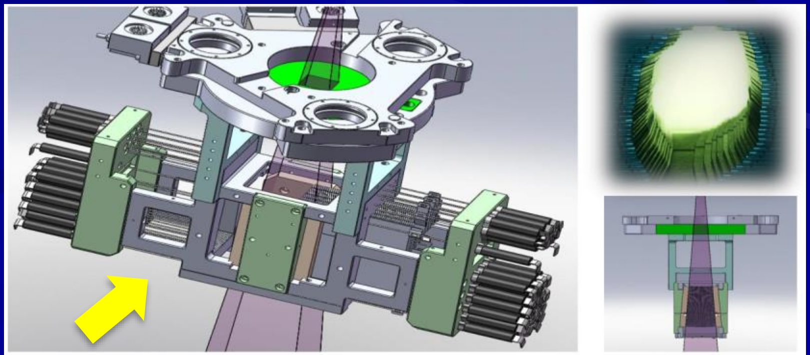
G4

M6

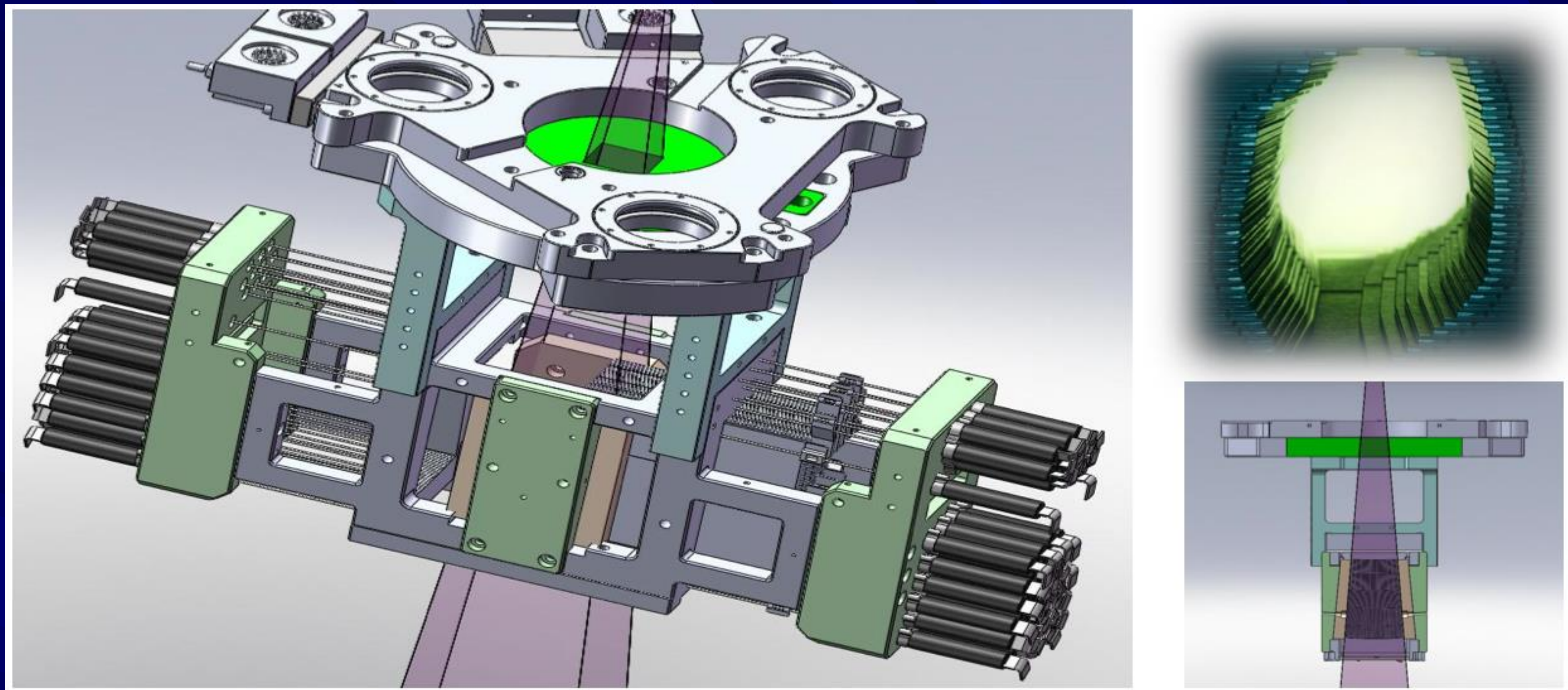
Fixed Cones



IRIS



MLC



* 41 leaf pairs

* 2.5 mm leaf thickness @ 800 mm
* 120 mm x 100 mm field size
* 90.0 mm leaf height
* 0.5 mm leaf position accuracy
* 0.4 mm reproducibility

* Transmission: <0.3% avg (<0.5% max)
* Full leaf inter-digitation
* Full leaf over-travel
* Single Focus MLC

Cyberknife G4 -> M6

Digital Platform

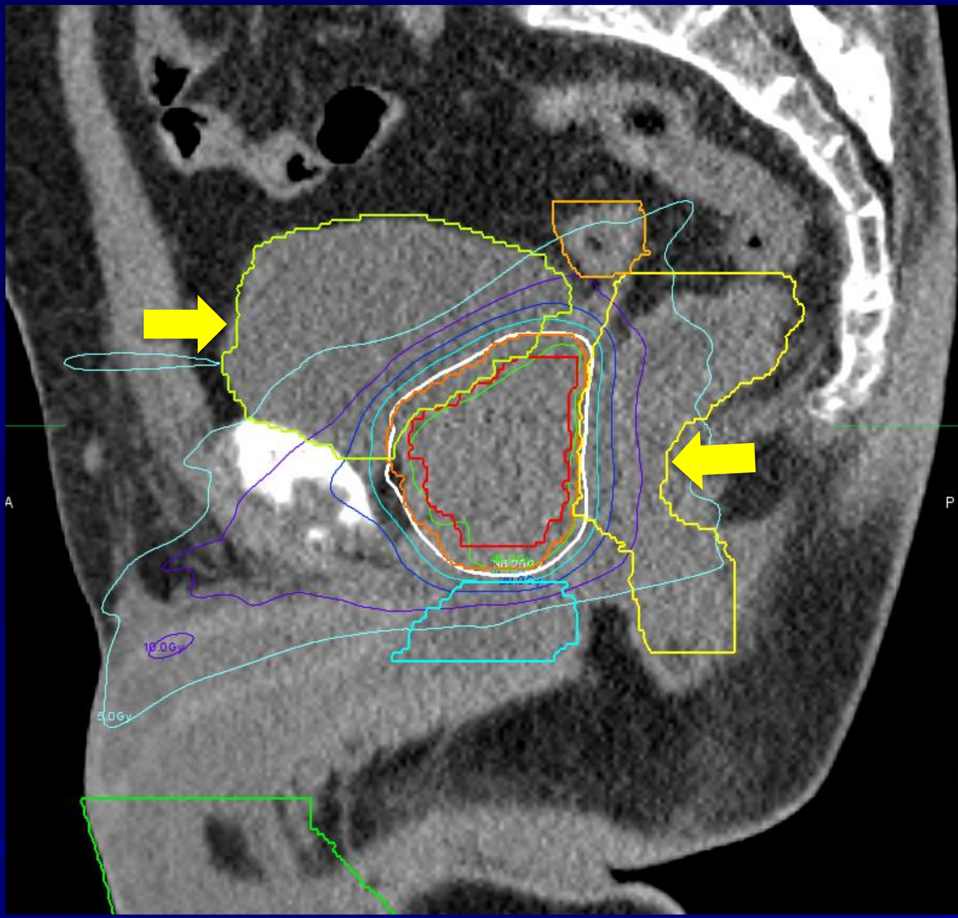
Different Robot position

MLC -> IMRT capable

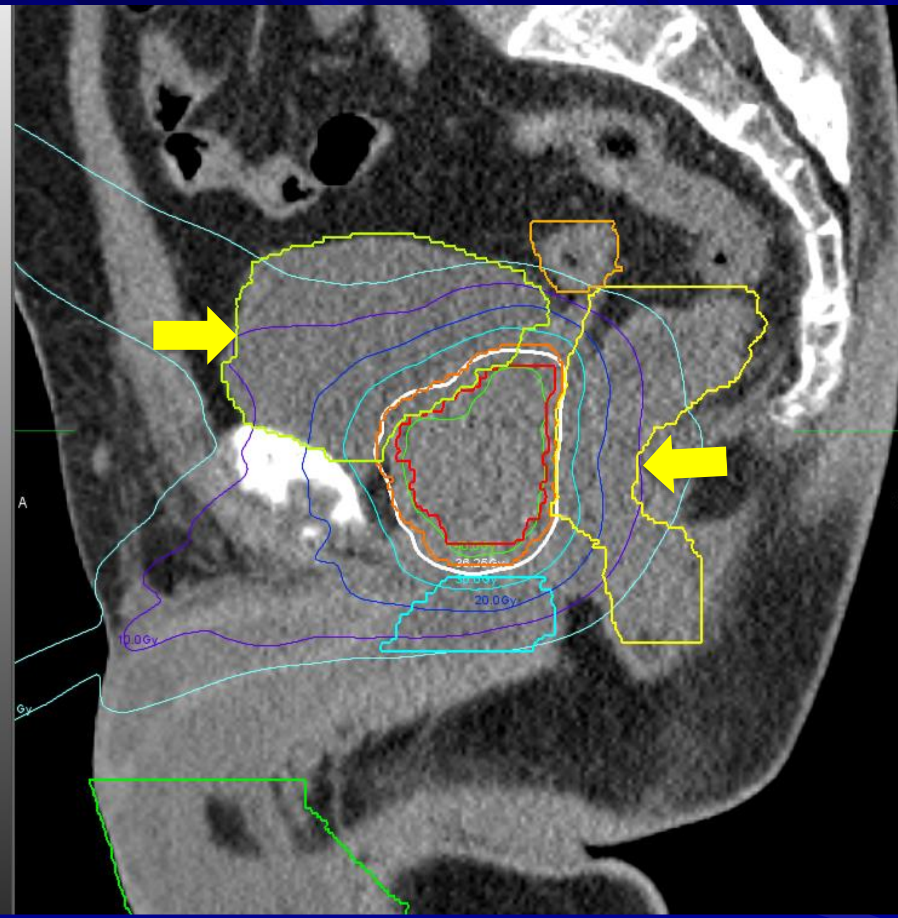
SBRT: faster, slightly better SBRT plan

IMRT: comparable with Linac based

SBRT Plan Comparison



MLC



Fixed Cones

CyberKnife Components & treatment

Motion management

Dosimetry

Quality Assurance

Case Specific Tracking Modalities

- Skull Tracking ----- Brain tumor
- X-site (spine) Tracking ----- Spine tumor
- Fiducial Tracking   ----- Soft tissue
- Synchrony Tracking ----- Moving Soft tissue
- X-sight Lung ---- Moving visible lung tumor
- Lung Optimization Treatment --- a full set of tracking for lung tumor without fiducial

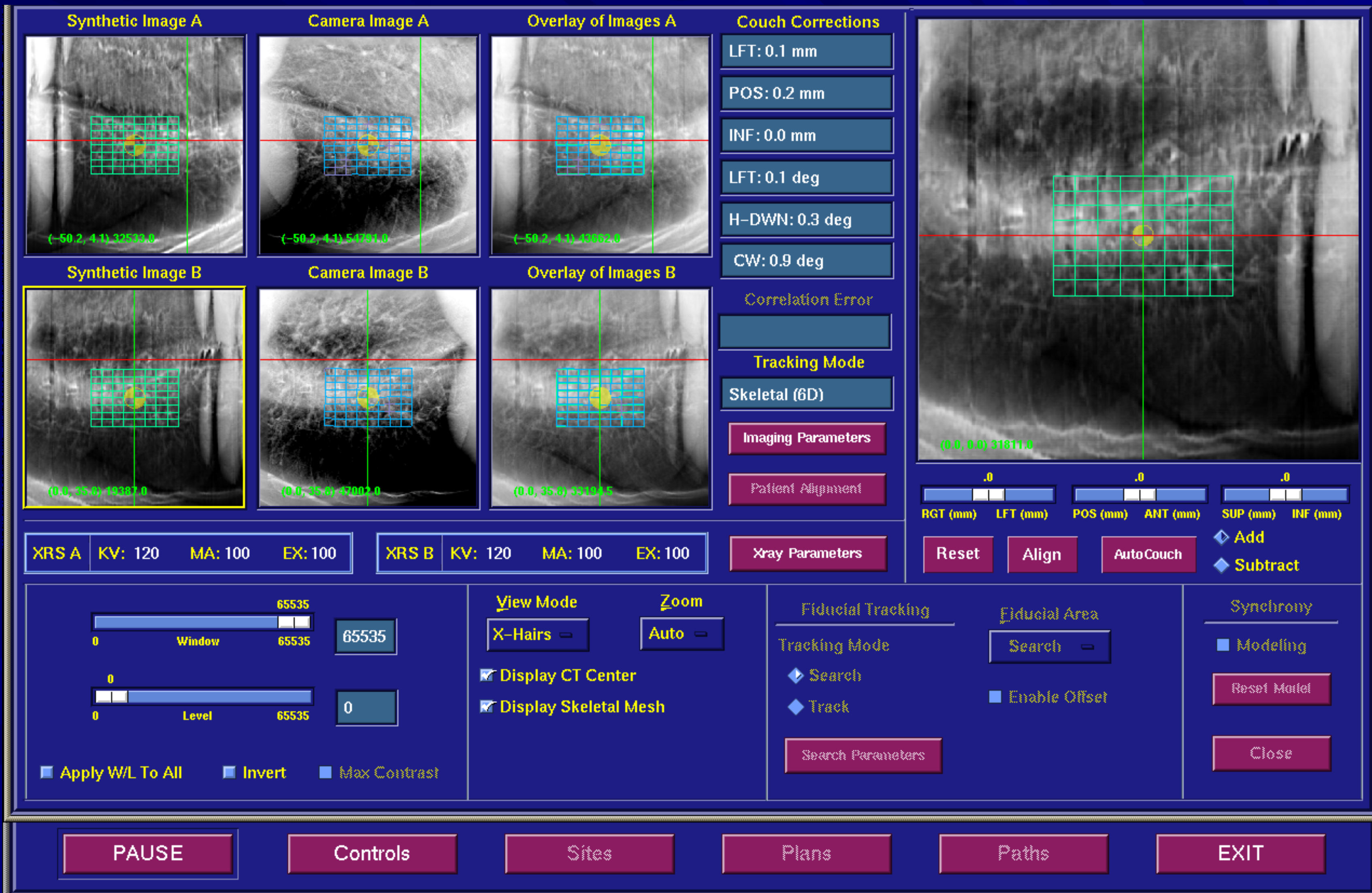
Tracking Methodology

- DRR (Digitally Reconstructed Radiographs) library used as references.
- X-ray images acquired in real time
- Registration between 2 DRR and X-ray images
- The patient’s rigid transformation calculated

Skull Tracking and Correction

Accuracy - Overall translation error ~ 0.5mm, rotation error ~ 0.5 degree.

Spinal Tracking and Correction



Special application: Bony Structures

Fiducial Tracking and Correction

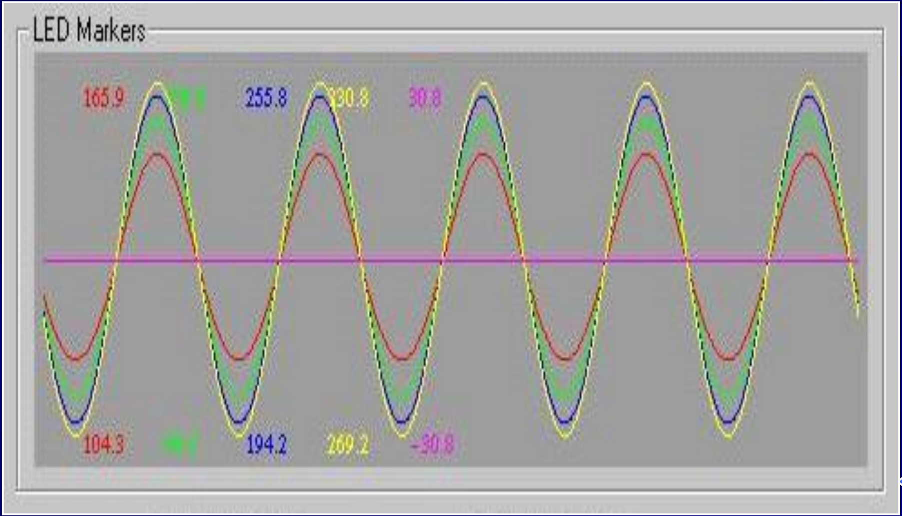
Special application: Surgical Clips

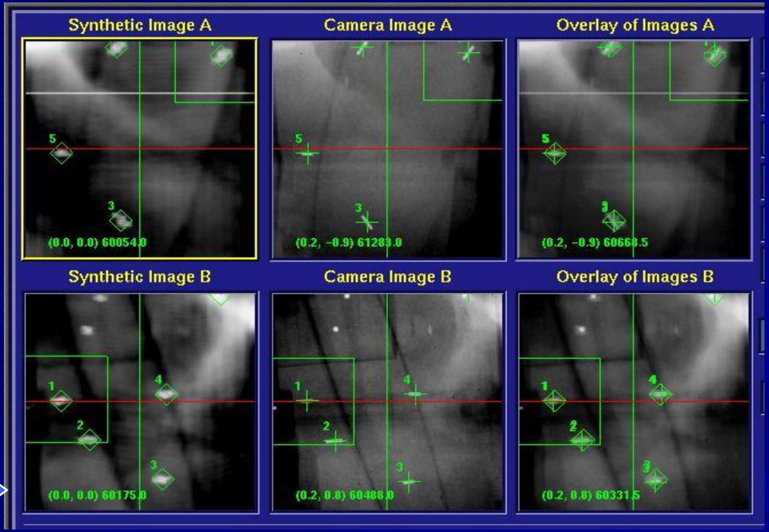
Tumor Respiratory Motion Consideration

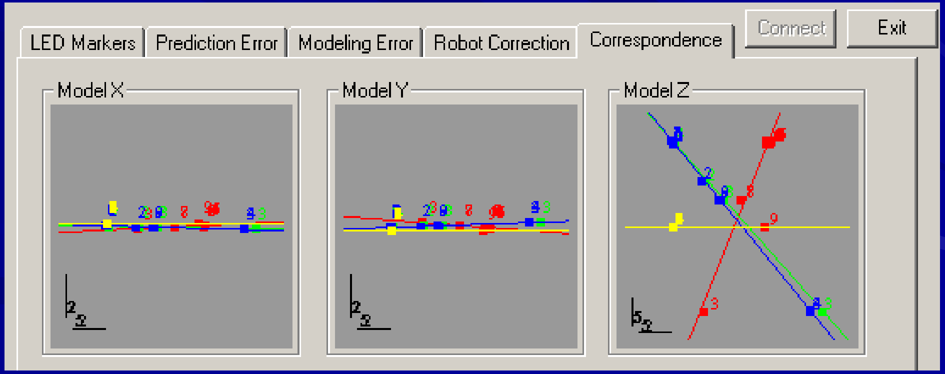
Breath Hold

Gating

Synchrony Motion Tracking and real-time Correction

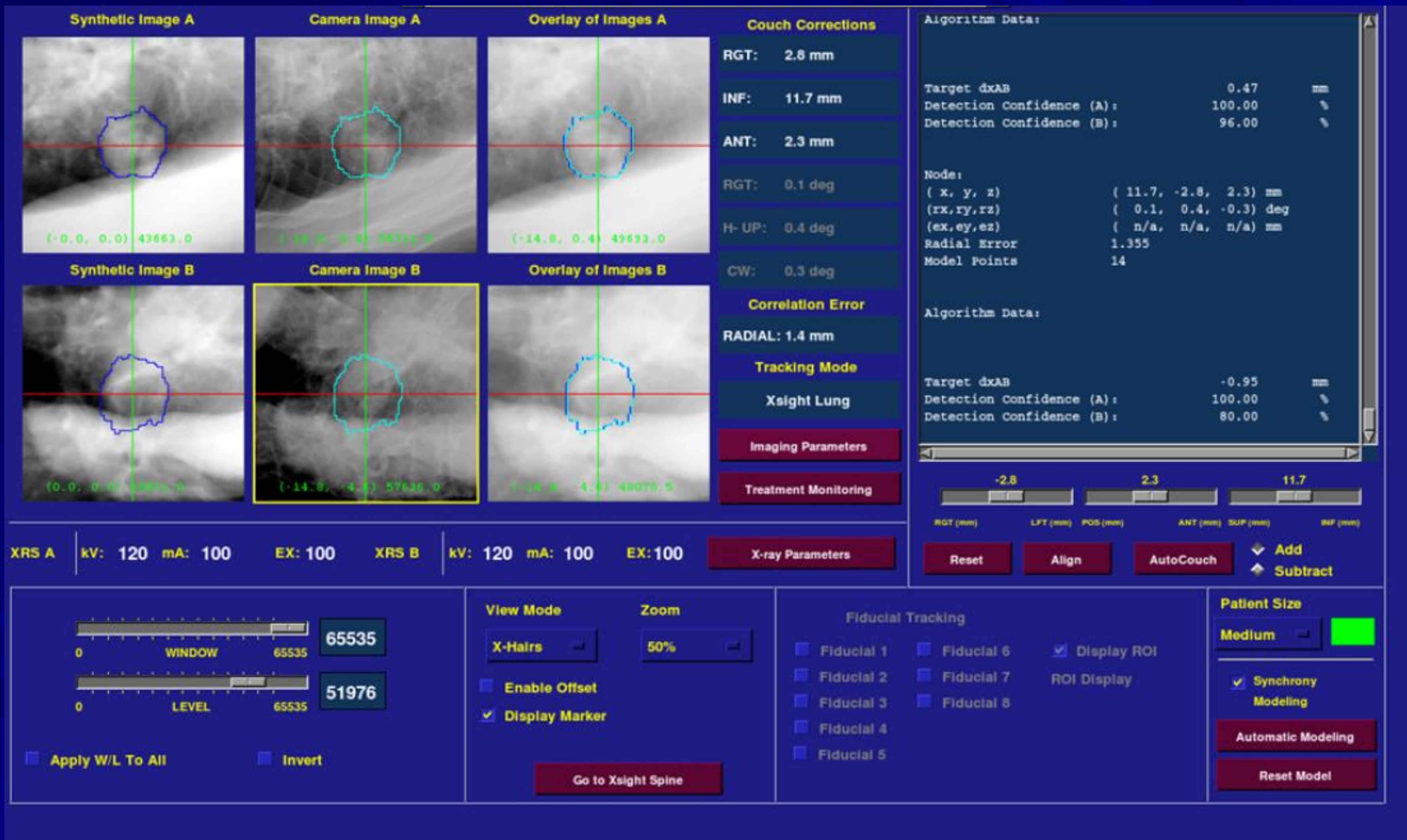






Synchrony Motion Tracking and real-time Correction

Xsight-Lung Tracking and real-time Correction

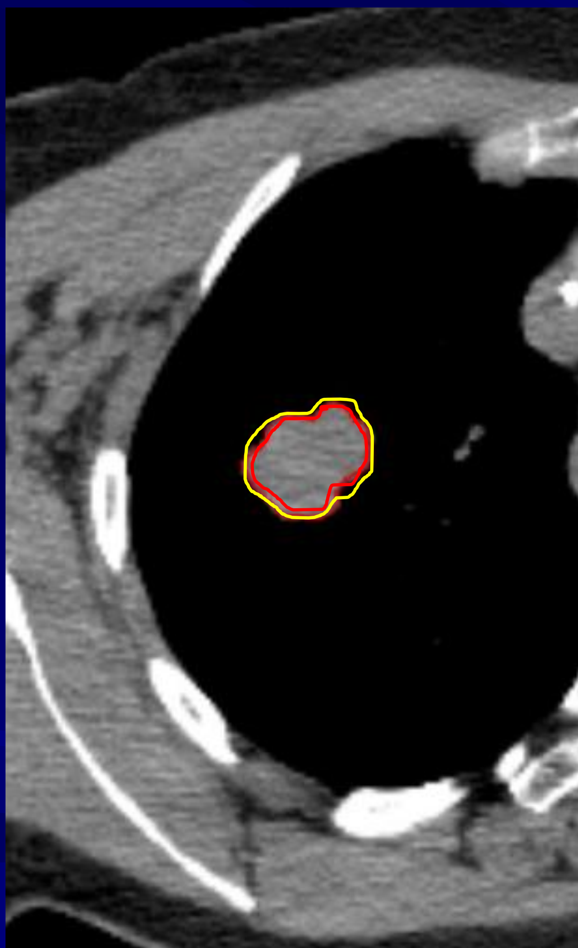


Special application: Sternum, Metal Stent, Large Calcification

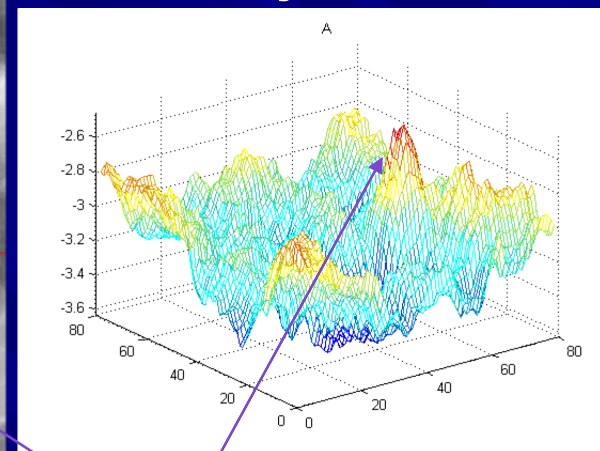
Lung tumor tracking without fiducials

Xsight® Lung Tracking

Radiosurgical margins



Similarity Measure

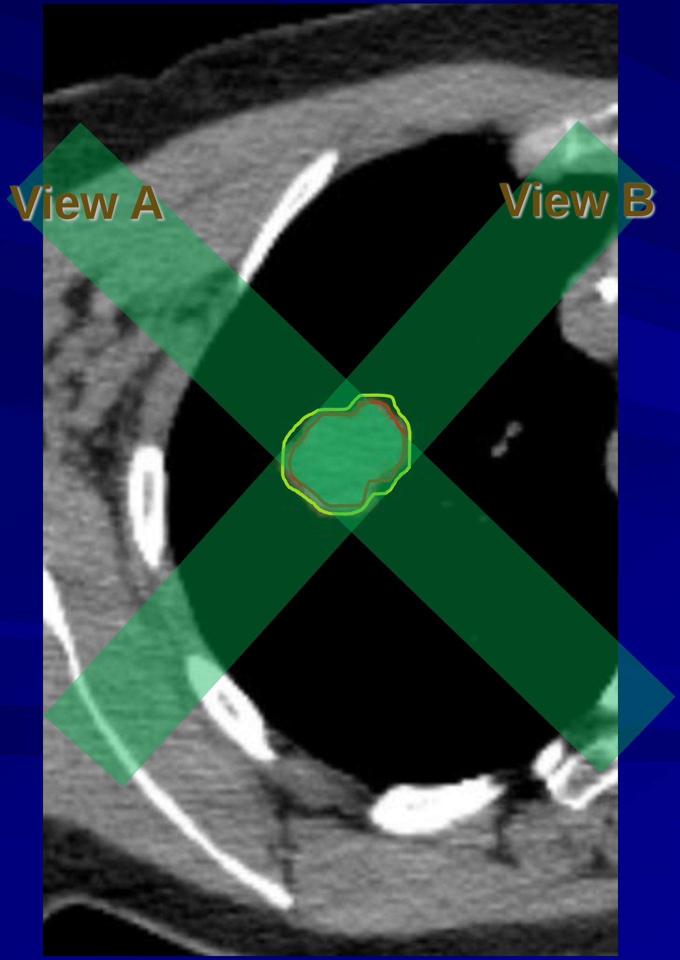


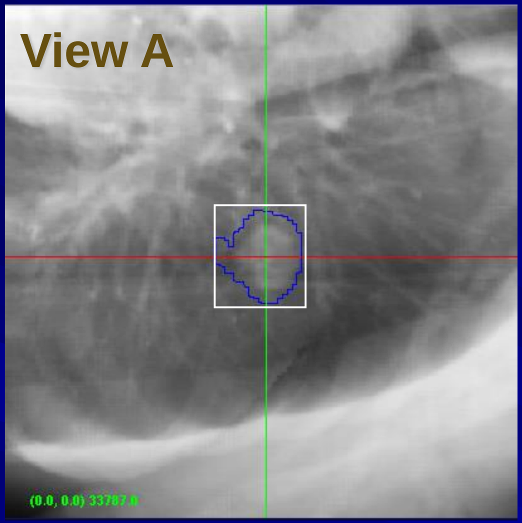
Maximum similarity

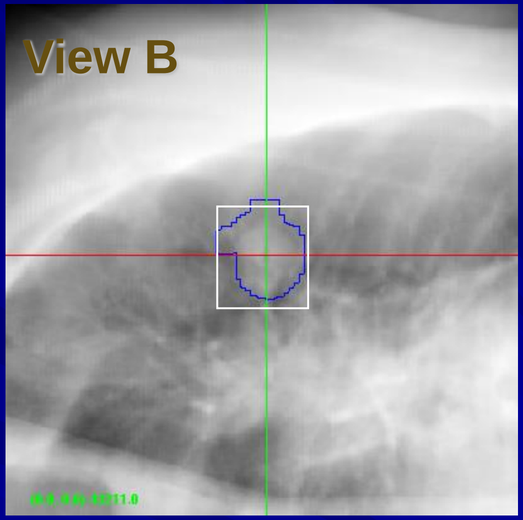
Lung tumor tracking without fiducials

Xsight® Lung Tracking

Radiosurgical margins



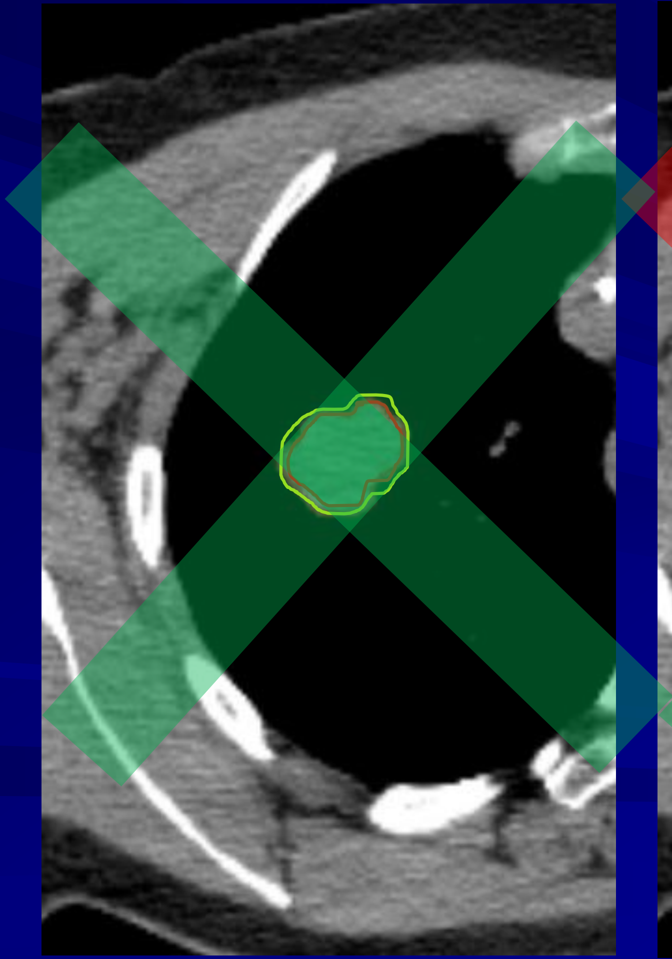




Lung tumor tracking without fiducials

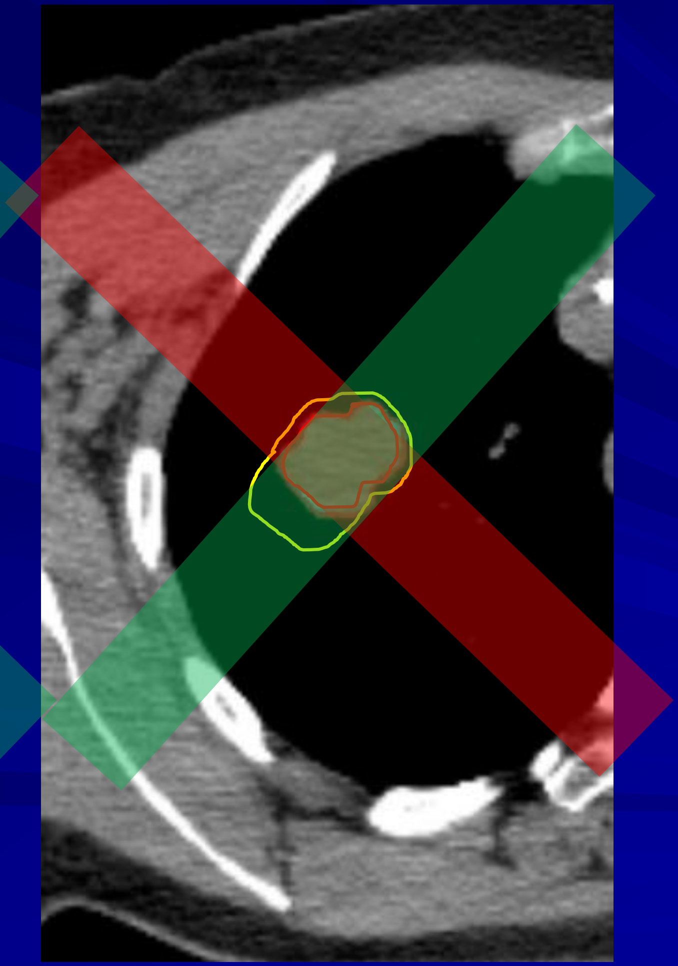
Xsight® Lung Tracking

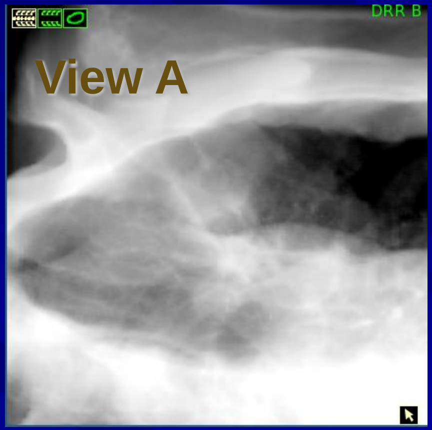
Radiosurgical margins

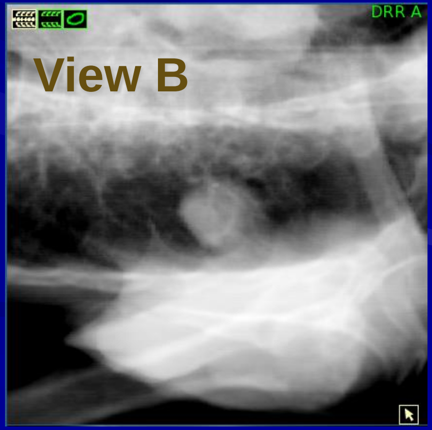


1-View Tracking*

ITV expansion in non-tracked direction





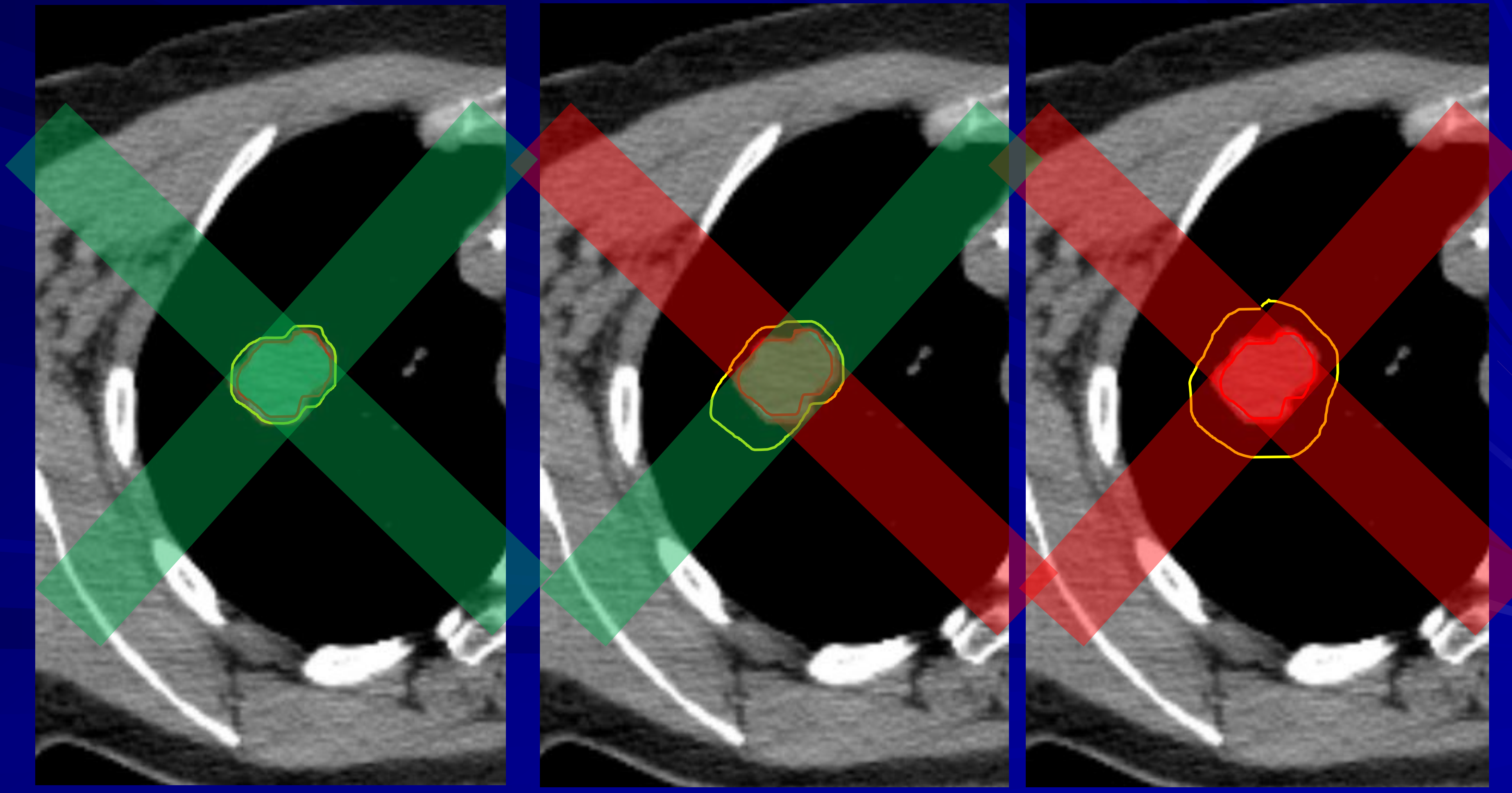


Lung tumor tracking without fiducials

Xsight® Lung Tracking
Radiosurgical margins

1-View Tracking*
ITV expansion in non-tracked direction

*0-View Tracking**
ITV expansion in all directions



Targeting Accuracy

- Mechanical accuracy
  - 0.12 mm (Kuka Specification 2004)[1]
- Targeting accuracy for targets not affected by respiration
  - 0.95 mm (Xsight® Specification)
  - 0.52 +/- 0.22 mm (Muacevic et. Al. 2006)[2]
  - 0.49 +/- 0.22 mm (Ho et. al. 2008)[3]
  - 0.4 +- 0.2 mm (Antypas and Pantelis 2008)[4]
  - 0.47 +- 0.24 mm (Drexler & Furweger 2009)[5]
- Targeting accuracy for targets that move with respiration
  - 1.5 mm (Synchrony® Respiratory Tracking System specification)
  - 0.70 +/- 0.33 mm (Dieterich et. Al. 2004)[6]
  - 0.47 +- 0.24 mm (Drexler and Furweger 2009)[5]

1 Kuka KR240-2 Specification 04.2004.05

2 Muacevic A, et. al. Technical description, phantom accuracy and clinical feasibility for fiducial-free frameless real-time image-guided spinal radiosurgery. J Neurosurg Spine. 2006 Oct;5(4):303-12.

3 Ho AK, et al. A study of the accuracy of Cyberknife spinal radiosurgery using skeletal structure tracking. Neurosurgery 2007;60:147-156.

4 Antypas C and Pantelis E. Performance evaluation of a CyberKnife G4 image-guided robotic stereotactic radiosurgery system. Phys Med Biol 2008;53:4697-4718

5 Drexler and Furweger. Quality assurance of a robotic, image guided radiosurgery system. WC 2009, IFMBE Proceedings 25/I, 492-495, 2009

6 Dieterich S, et. al. The CyberKnife Synchrony Respiratory Tracking System: Evaluation of Systematic Targeting Uncertainty. White paper 2004.

CyberKnife Components & treatment

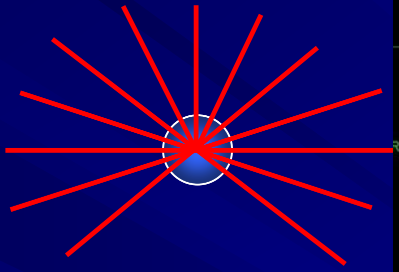
Motion management

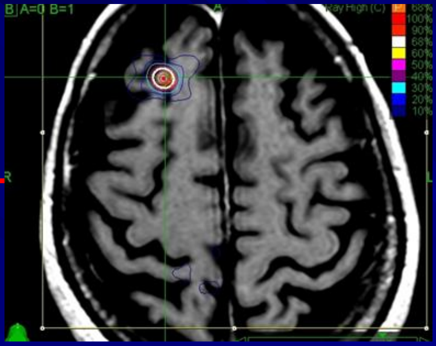
Dosimetry

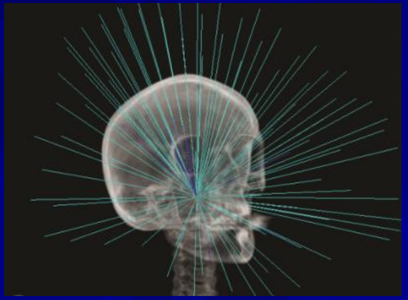
Quality Assurance

Dosimetry: various beam arrangements

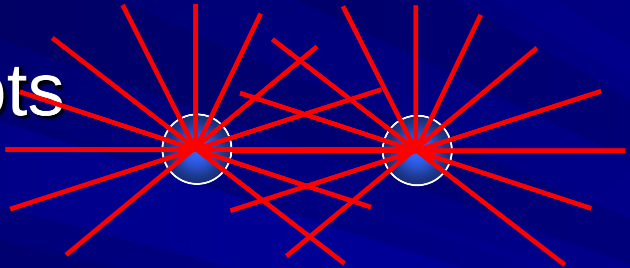
- Isocentric
  - -- single shot

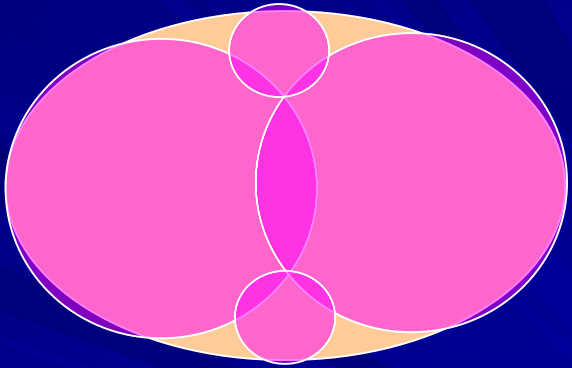




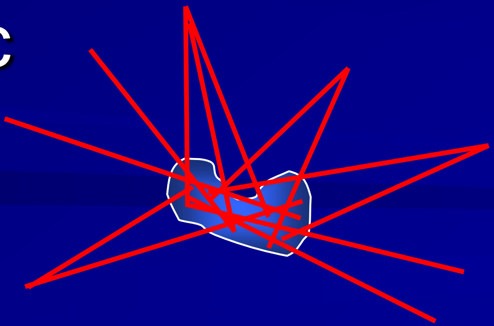


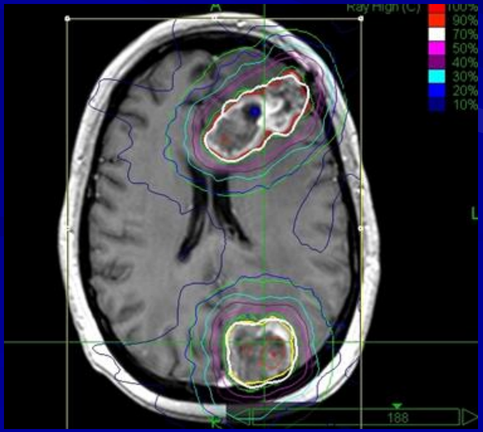
  - -- multiple shots



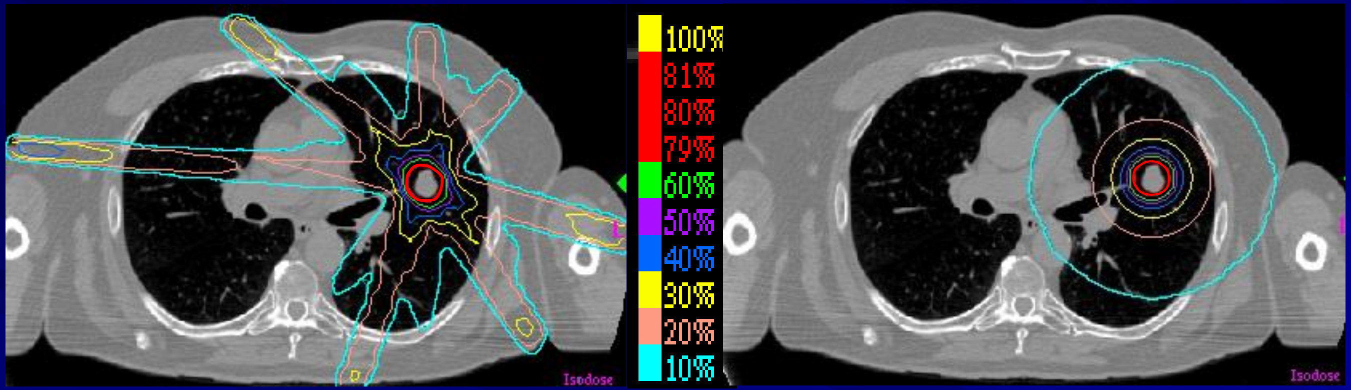


- Non-isocentric
  - -- Conformal



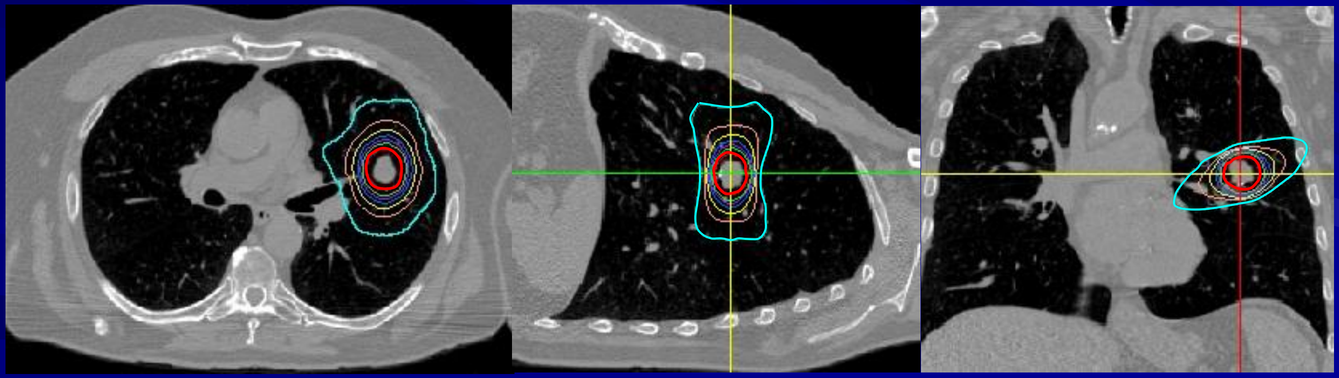


Non-coplanar beams



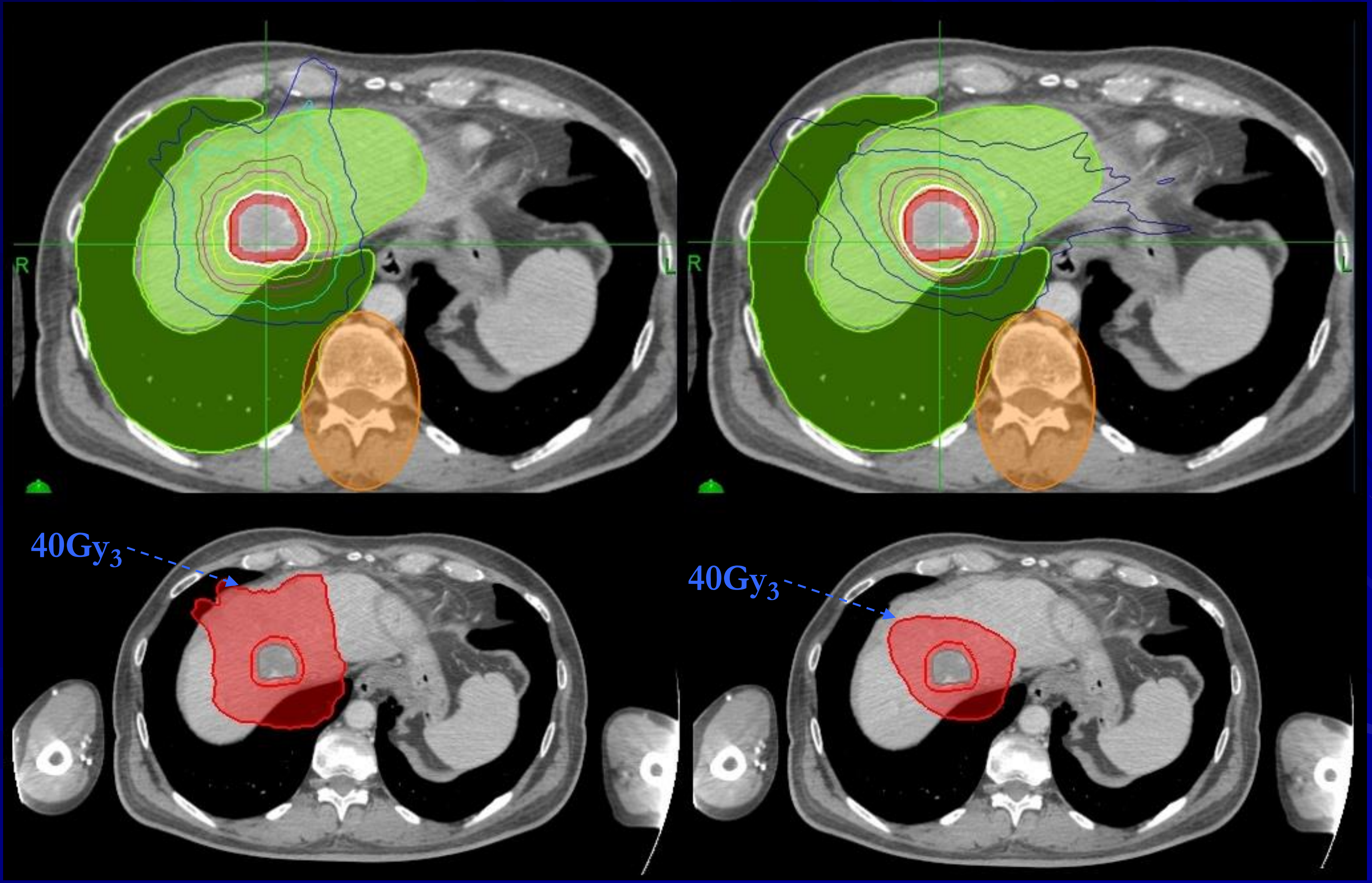
7 Beam IMRT

"Tomo", single Plane RT



Cyberknife – 80 Beam SRS

Applications– Plan Evaluation



Conformal Non-isocentric Plan

Fast Fall-off Isocentric Plan

CyberKnife Components & treatment

Motion management

Dosimetry

Quality Assurance

Quality Assurance

- End 2 End test
- BB test
- AQA
- Beam analysis
- Plan dose verification
- Image system test
- Daily, Monthly, Quarterly and Annually QA

QA guidelines: TG 135: Quality assurance for robotic radiosurgery

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

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 ± 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

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.	Adjust calibration if >1% difference is found
	Beam data checks on at least three collimators, including largest and smallest collimator (TPR or PDD, OCR, output factors).	To be decided by user
	Dose output linearity to lowest MU/beam used.	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.	TG 53 (Ref. 26)
	CT QA (in addition to monthly).	See TG 66 (Ref. 29)
	Data security and verification.	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

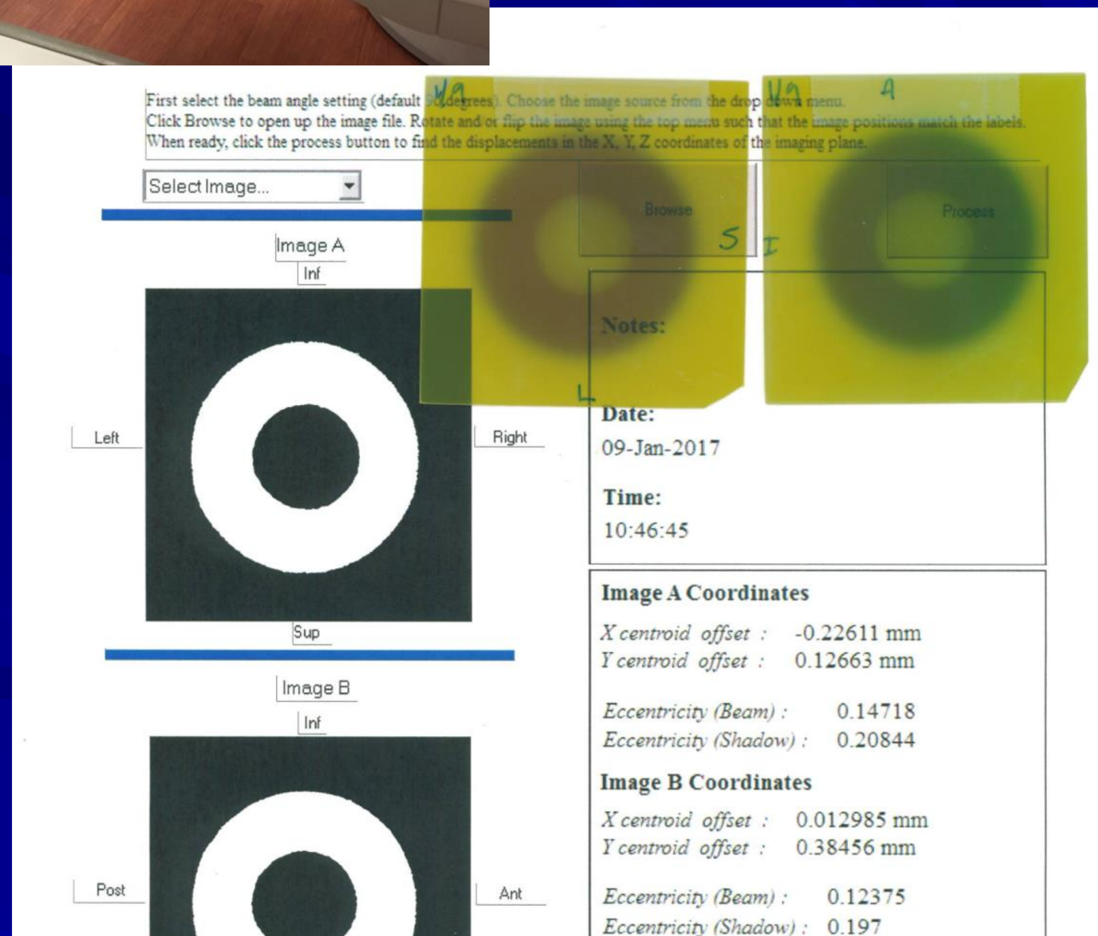
QA guidelines: AAPM-RSS Medical Physics Practice Guideline 9.a. for SRS – SBRT(Draft)

Table 2: Minimum equipment QA and tolerances for robotic linac systems

Frequency	Test	Tolerance
Daily* **On days of clinical use*	Head laser alignment check	1.0 mm
	Safety interlocks	Functional
	Automatic QA (AQA) test* **If the clinic has both fixed cones and Iris™ collimator, the AQA test should alternate between fixed cones and Iris™, with each system tested at least weekly*	Total targeting ≤ 1.0 mm from baseline, not exceeding manufacturer's specification
	Accelerator output constancy	± 3%
Monthly	Energy constancy	± 2%
	Beam symmetry, relative	± 3% for 40 mm field, ± 4% for 60 mm field,
	Accelerator output constancy	± 2%
	Imager alignment	1mm or center pixels ± 2 pixels
	Iris Field size spot check	0.5 mm, 3 or more field sizes ≥ 10 mm
	Picket fence for MLC *(if applicable)*	Visual check
Quarterly	E2E localization assessment (Each tracking mode used clinically)	1.0 mm static target, 1.5 mm motion tracking
Annually	Emergency Power Off (EPO) button, safety interlocks	Functional
	Accelerator output	± 2.0%
	MU linearity (>10 MU to highest MU used clinically)	± 2%
	Path verification	≤0.5 mm maximum per node, ≤0.3 mm average
	Imager kVp accuracy, mA station exposure linearity, isopost alignment with center pixel	± 10%, ± 20%, and 1 mm respectively
	Beam laser and radiation beam alignment for cone, Iris and MLC	0.5 mm from baseline
	AQA baseline	Re-check AQA baseline
	Beam data verification - Relative output factors for cones, Iris and/or MLC covering the range used clinically	± 2% from baseline for > 1.0 cm apertures, ± 5% from baseline for ≤ 1.0 cm apertures

Morning QA - Output

Morning QA – AQA W-L test



First select the beam angle setting (default 90 degrees). Choose the image source from the drop down menu.
Click Browse to open up the image file. Rotate and/or flip the image using the top menu such that the image positions match the labels.
When ready, click the process button to find the displacements in the X, Y, Z coordinates of the imaging plane.

Select Image...

Browse

Process

Image A

Inf

Left

Right

Sup

Image B

Inf

Post

Ant

Notes:

Date:
09-Jan-2017

Time:
10:46:45

Image A Coordinates

X centroid offset : -0.22611 mm
Y centroid offset : 0.12663 mm

Eccentricity (Beam) : 0.14718
Eccentricity (Shadow) : 0.20844

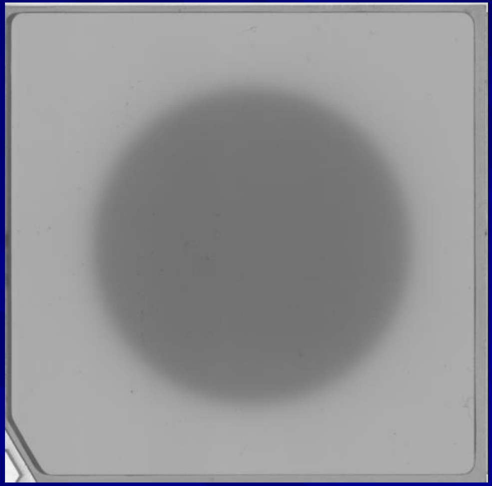
Image B Coordinates

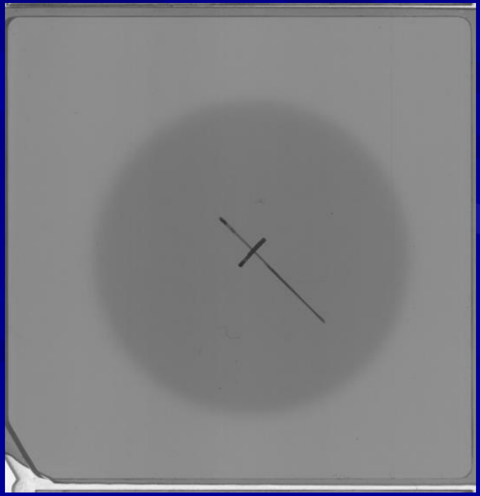
X centroid offset : 0.012985 mm
Y centroid offset : 0.38456 mm

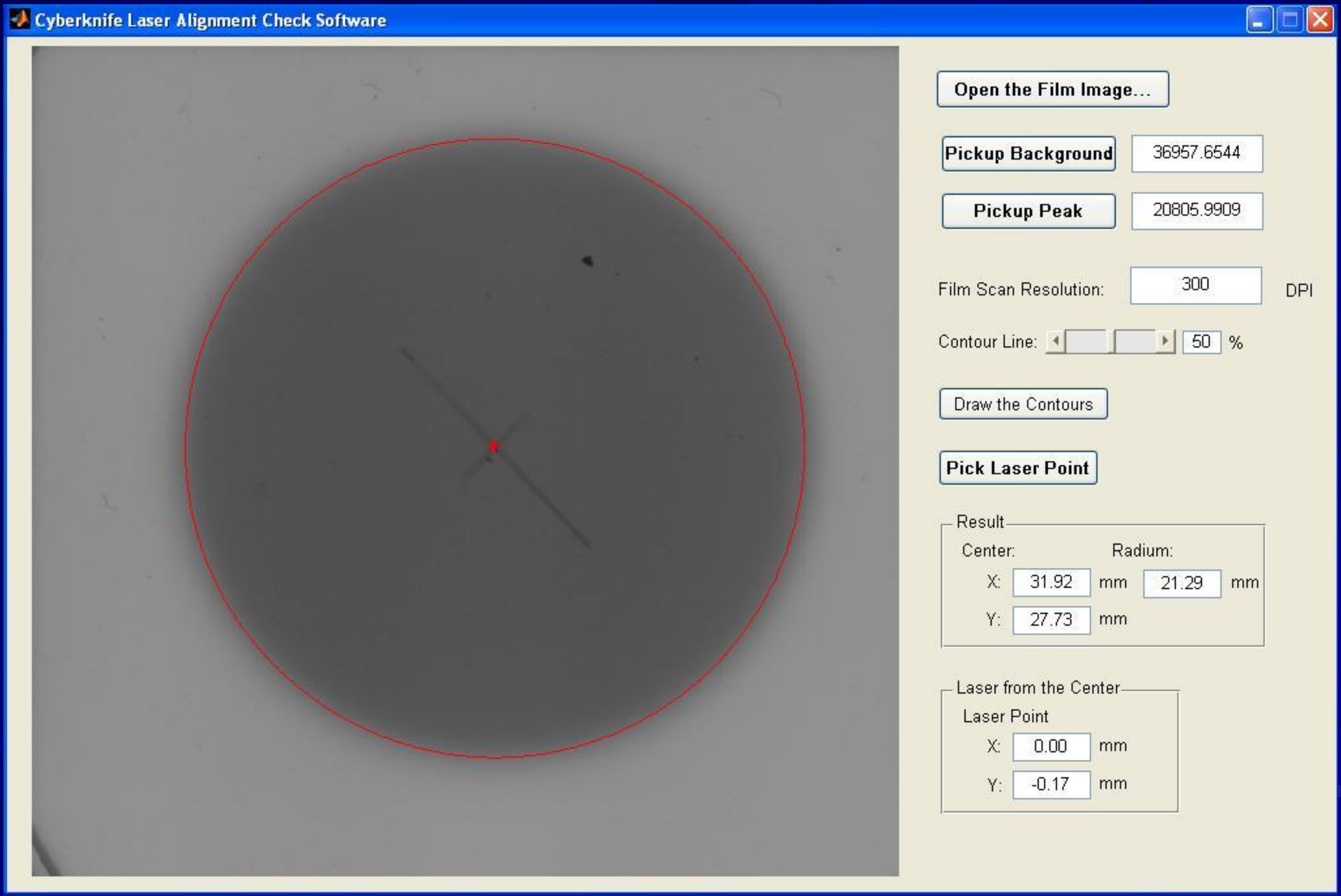
Eccentricity (Beam) : 0.12375
Eccentricity (Shadow) : 0.197

Monthly QA- Ouput/Energy

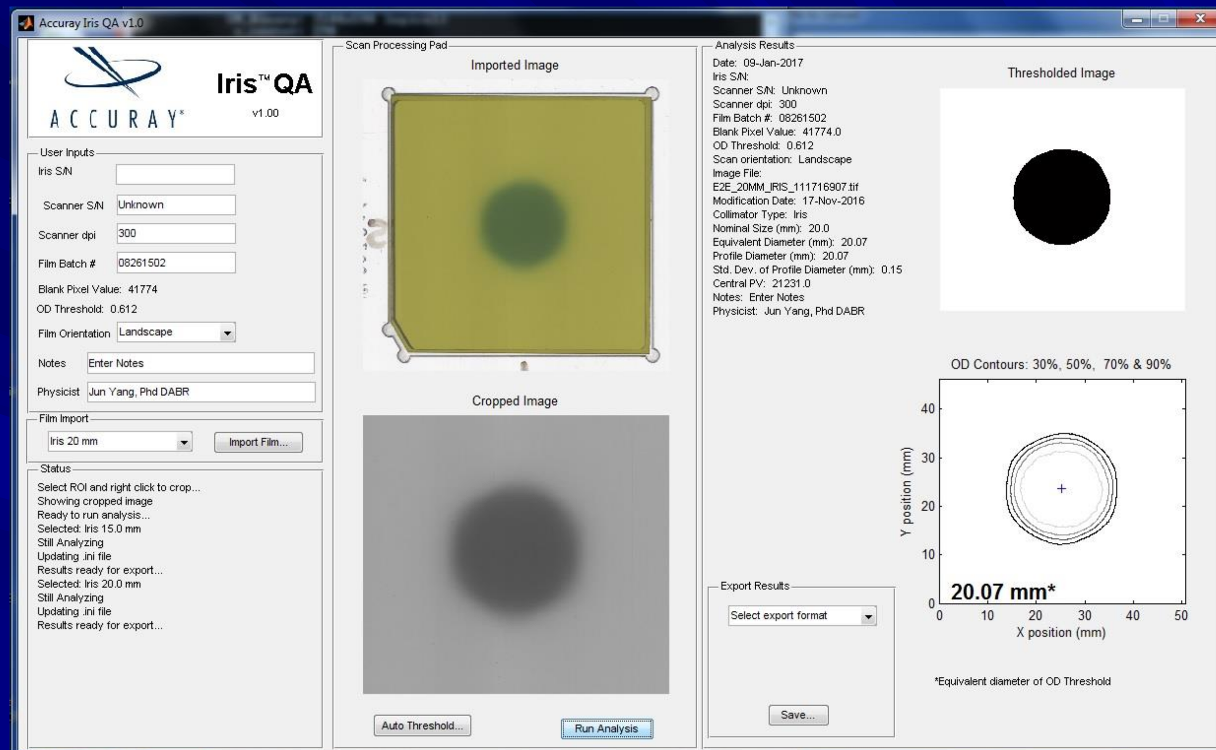
Monthly QA – Symmetry and Flatness/ Laser Alignment



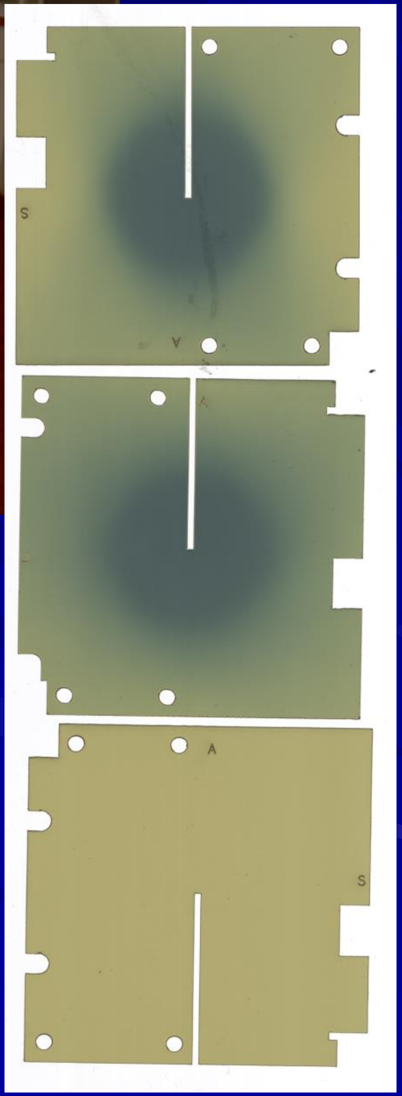



Cyberknife Laser Alignment Check Software
Open the Film Image...
Pickup Background
36957.6544
Pickup Peak
20805.9909
Film Scan Resolution:
300
DPI
Contour Line:
50
%
Draw the Contours
Pick Laser Point
Result
Center:
Radium:
X:
31.92
mm
21.29
mm
Y:
27.73
mm
Laser from the Center
Laser Point
X:
0.00
mm
Y:
-0.17
mm

Monthly QA – IRIS Collimator Field Sizes



Monthly QA – E2E



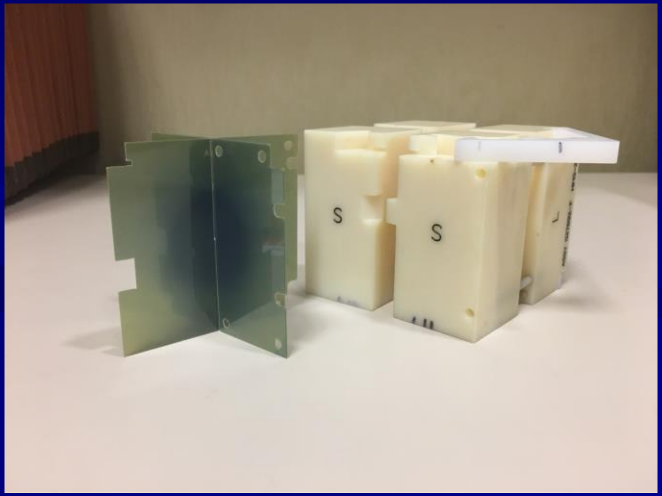
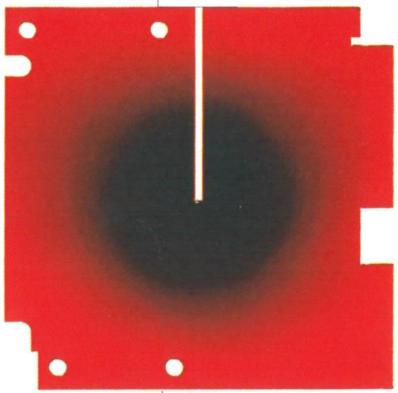


Image 1

Ant.

Left



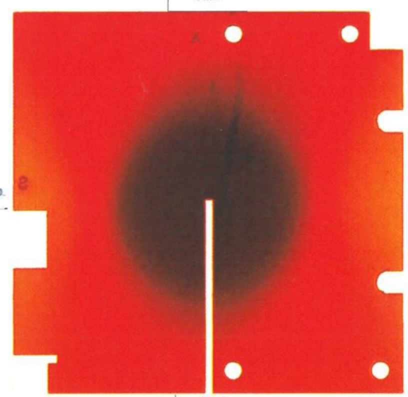
Right

Post.

Image 2

Ant.

Sup.



Inf.

Post.

ACCURAY

End-to-End (E2E) Film Analysis

Image 1 Threshold Area

Image 2 Threshold Area

Image 1 Threshold Area Information

Centroid Area:	140171
Pixels to Left:	376.13
Pixels to Top:	373.2
Eccentricity:	1.12

Image 2 Threshold Area Information

Centroid Area:	111116
Pixels to Left:	381.65
Pixels to Top:	375.96
Eccentricity:	1.36

Image 1 Multiple Threshold Contours

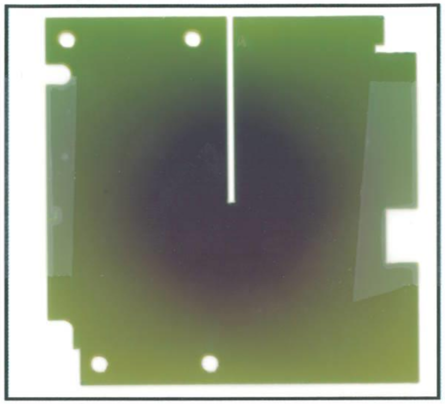
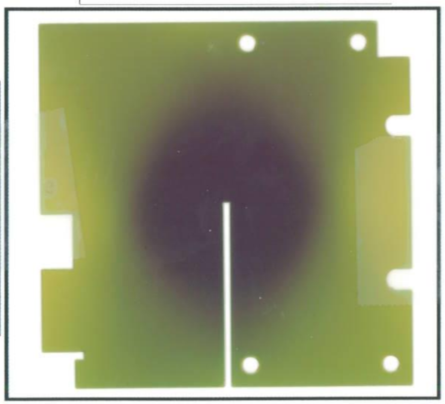


Image 2 Multiple Threshold Contours



E2E Reference

Test:	IRIS FUD
Date:	11/17/2016
Film Label:	
Scanner:	Epson 1680
Film Type:	EBT 2
Film Batch:	
Analysis Color	RED
Image Bit Depth:	48

Calibration Information

Hor pix/mm:	11.9
Vert pix/mm:	11.81
Sup. Pos mm:	31.75
Ant. Pos mm:	31.75
Left Pos mm:	31.75

Pixel Measurement

Contour Threshold: 25272

Minimum: 19644

BG Film: 45489

Image 1 (A/L Image) Info

mm from left edge:	31.61
mm from anterior edge:	31.6
contour area/ball area:	1.26

Image 2 (A/S Image) Info

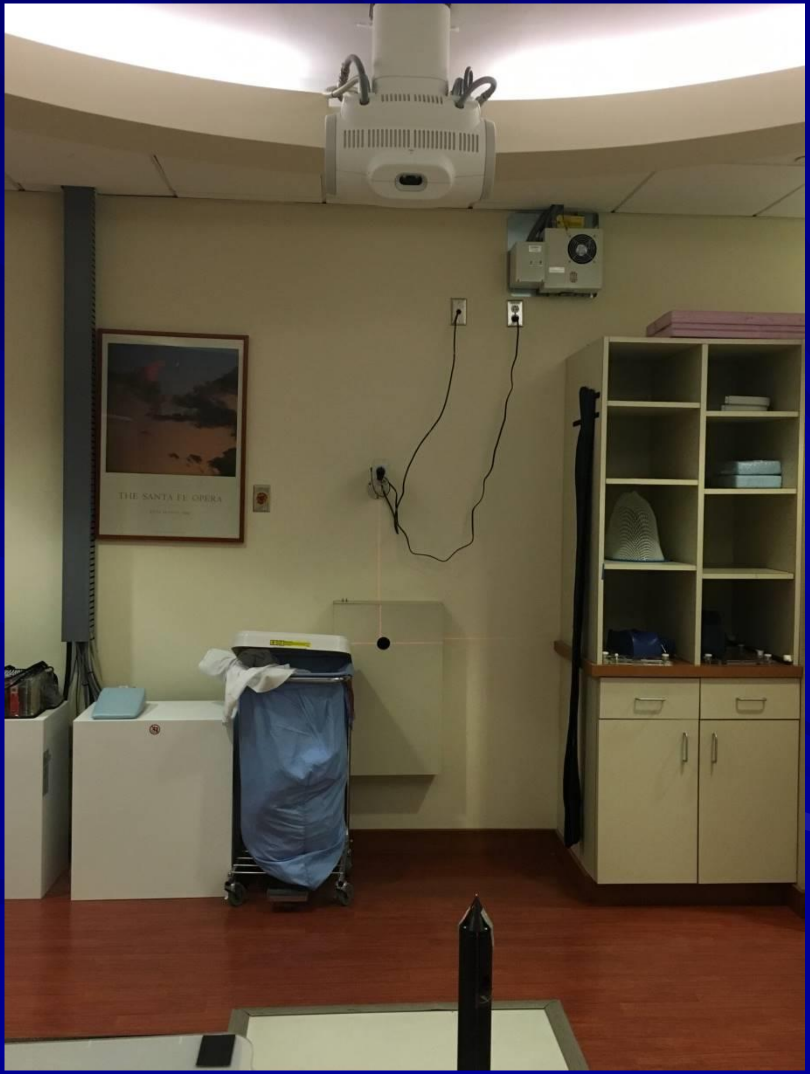
mm from superior edge:	32.07
mm from anterior edge:	31.83
contour area/ball area:	1

Error Information

left error mm:	0.14
anterior error mm (A/L image):	0.15
superior error mm:	-0.32
anterior error mm (A/S image):	-0.08
average anterior error mm:	0.03
TOTAL TARGETING ERROR mm:	0.35

70% Contour Level

Monthly QA – Imaging Center



Which of these following tracking modalities used in the lung cancer treatment can accommodate expiratory motion?

1 Xsight-lung tracking

2 Spine tracking

3 Synchrony Tracking (using fiducial)

4 Lung Optimization Treatment

A: 1, B: 1, 2, 3 C: 1, 3, 4 D: 1, 2, 3, 4

Ans: C only the spine tracking in the list uses bony information of spinal skeleton as tracking landmark.

Ref: TG135 “Report of AAPM TG 135: Quality assurance for robotic radiosurgery”

What is not true for Cyberknife

a. Allows multiple non-coplanar beams

b. Allows single isocentric or non-isocentric shots, but not multiple isocentric shots

c. Fully optimized with inverse planning

d. Allows motion correction during treatment delivery

- Answer: B

Ref:Jun Yang, John Lamond, Jing Feng, Xiaodong Wu, Rachelle Lanciano, and Luther W. Brady "CyberKnife System" Chapter of S Lo, MD etc, "Stereotactic Body Radiation Therapy" Springer Press, 2012, pp 37-52

Thanks