QA for In Room Imaging: The Interface of Hardware, Software, and Patients

Kristy K. Brock, PhD, DABR

Associate Professor
Department of Radiation Oncology
Department of Biomedical Engineering
University of Michigan

Acknowledgements

Princess Margaret Cancer Centre– slides and eye candy movies

- David Jaffray, PhD
- Jean-Pierre Bissonnette, PhD
- Douglas Moseley, PhD

Why In Room Imaging?

- Patients are not consistent from day to day
  - Soft tissue moves and deforms
  - Tumor and critical normal tissue do not always track with bones and external surface
- Treating normal tissue is never beneficial
  - Reducing the volume of normal tissue treated often enables a higher dose to be delivered to the target
  - Higher doses often lead to better tumor control

Why In Room Imaging?

Simplified PTV margin recipe for dose - probability

To cover the CTV for 90% of the patients with the 95% isodose (analytical solution) :

PTV margin = 2.5 Σ + 0.7 σ

Σ = quadratic sum of SD of all preparation (systematic) errors
σ = quadratic sum of SD of all execution (random) errors

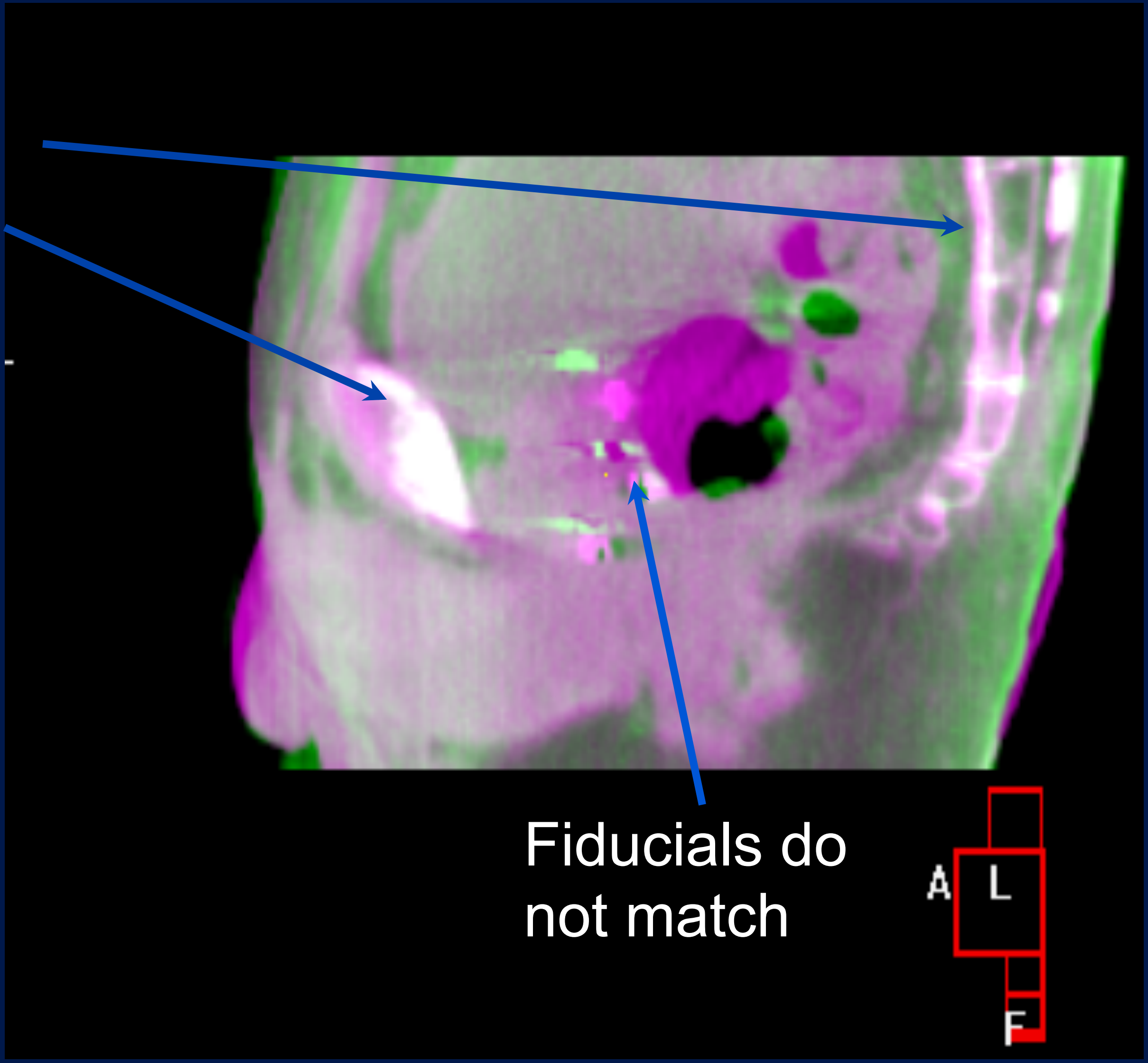
(van Herk et al, IJROBP 47: 1121-1135, 2000)

*For a big CTV with smooth shape, penumbra 5 mm

*Courtesy Tim Craig, Marcel van Herk

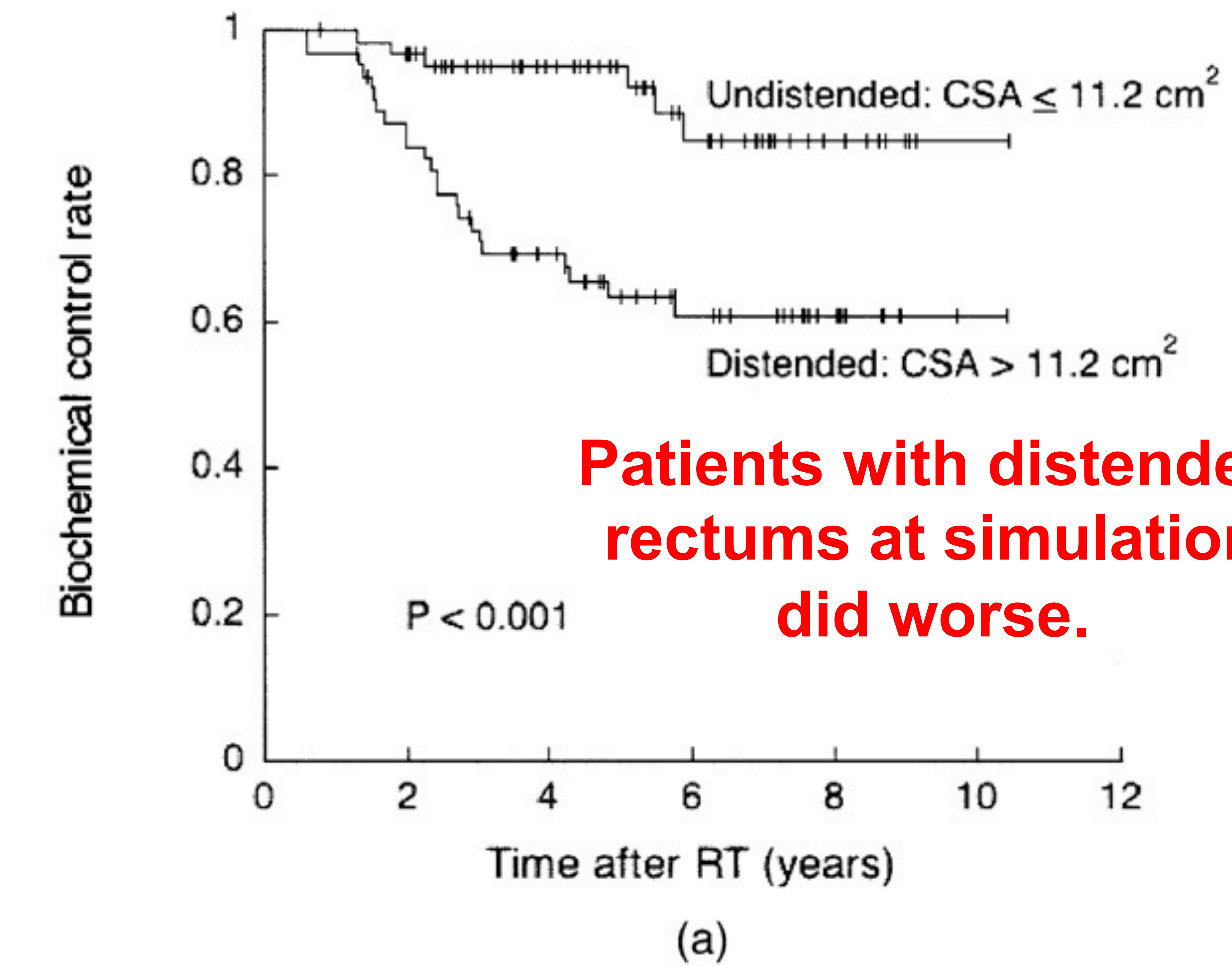
Internal Organ Motion

Bone matches



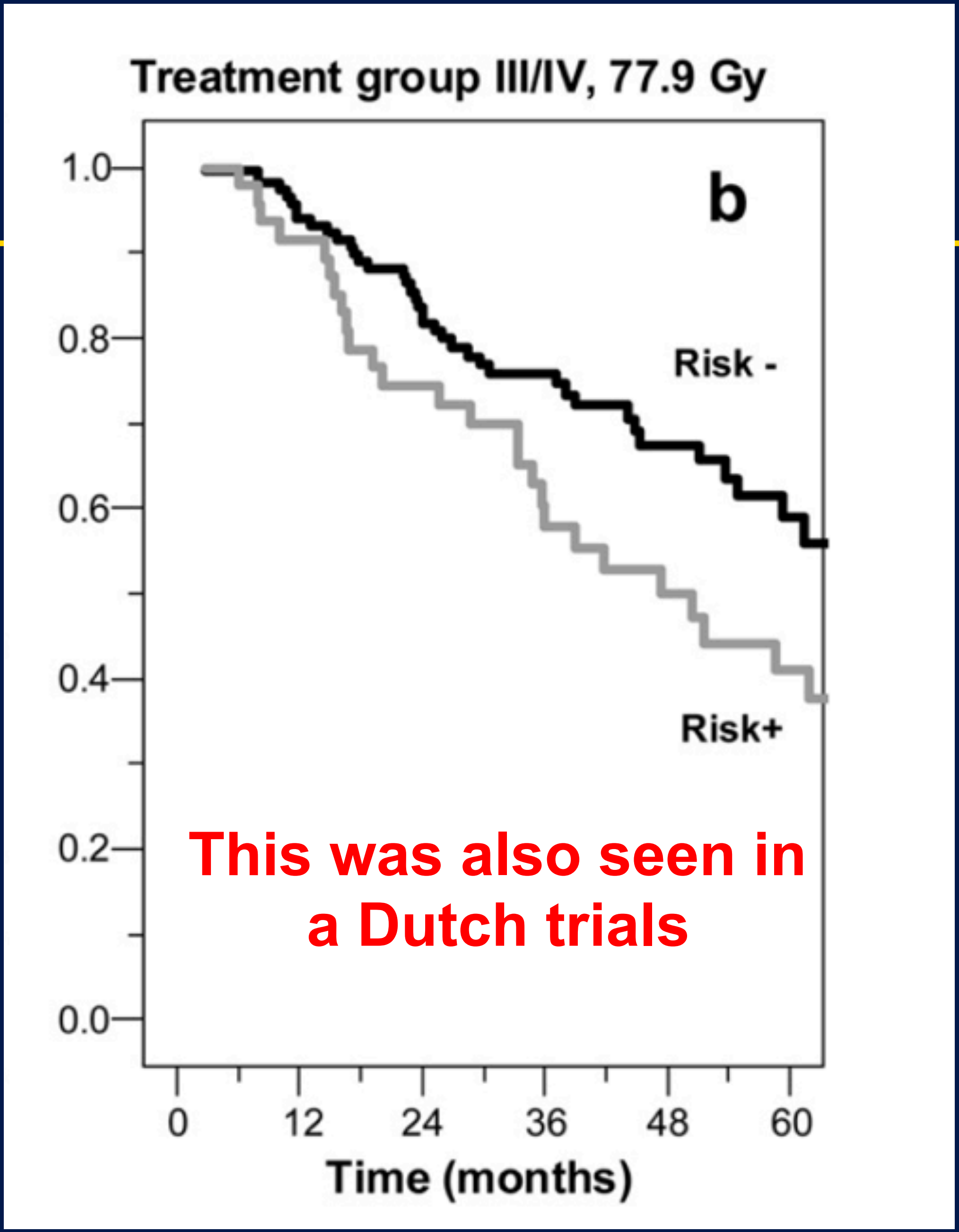
Fiducials do not match

Do these uncertainties have clinical impact?

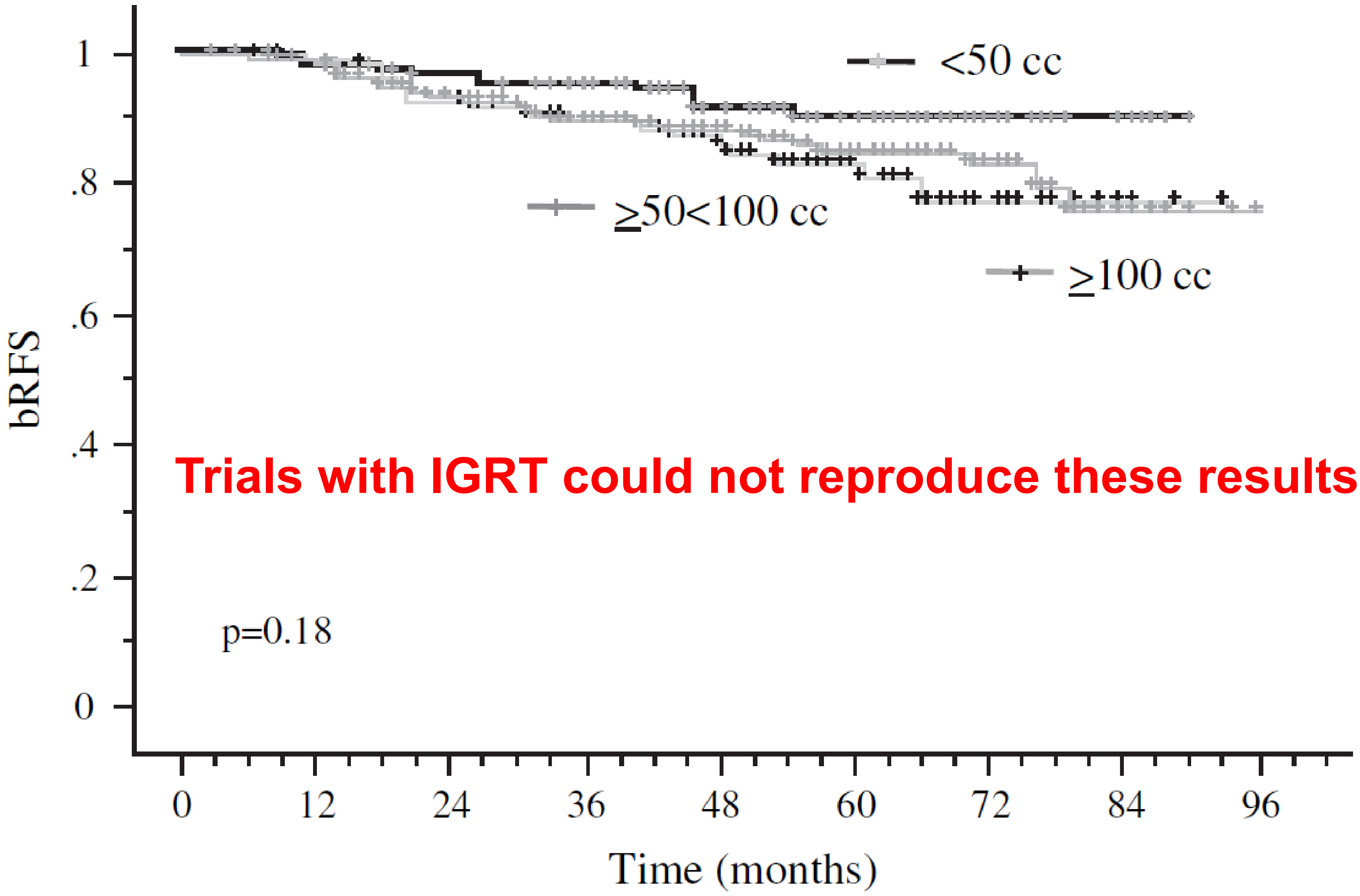


Patients with distended rectums at simulation did worse.

de Crevoisier et al, IJROBP 2005;62:965-973



Heemsbergen et al, IJROBP 2007;67:1418-1424

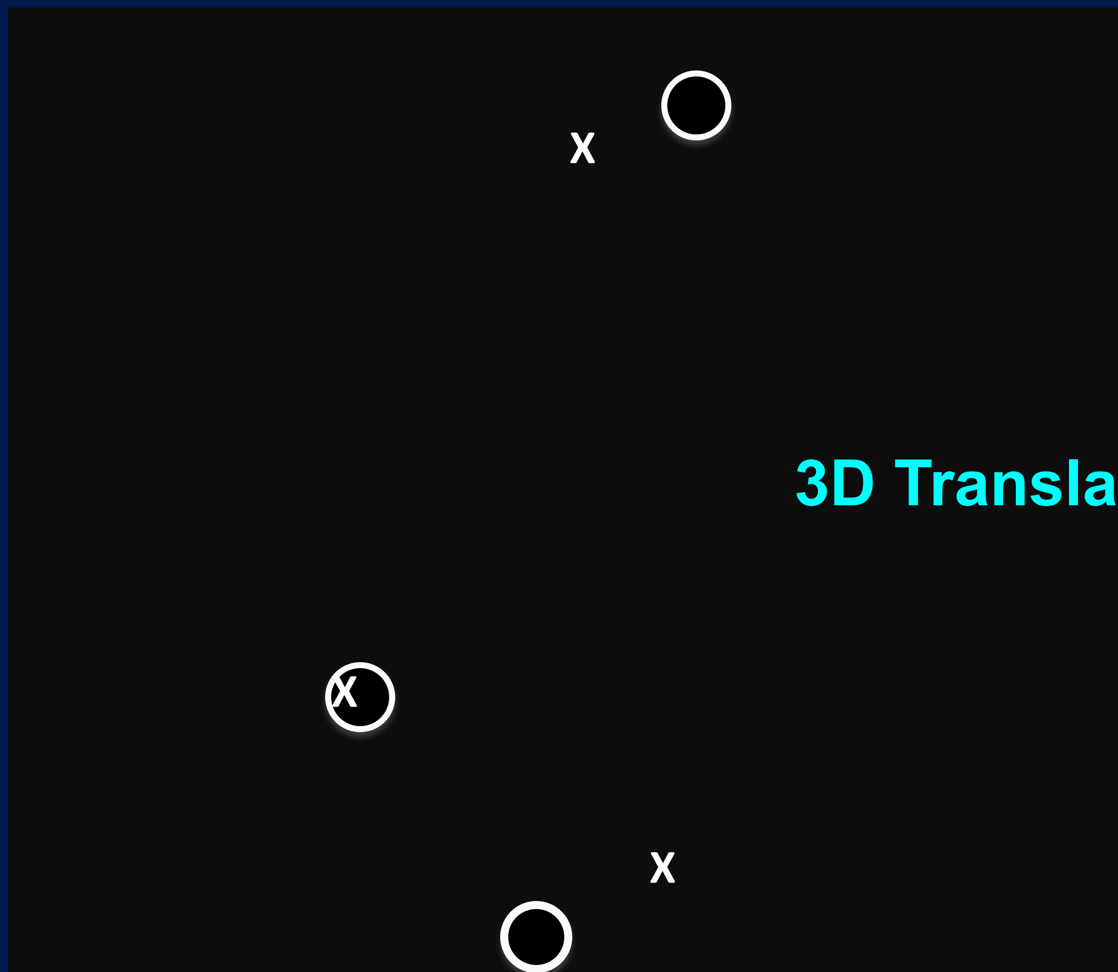


Trials with IGRT could not reproduce these results.

Kupelian et al, IJROBP 2008;70:1146-1150

Markers are not always enough

1 cm

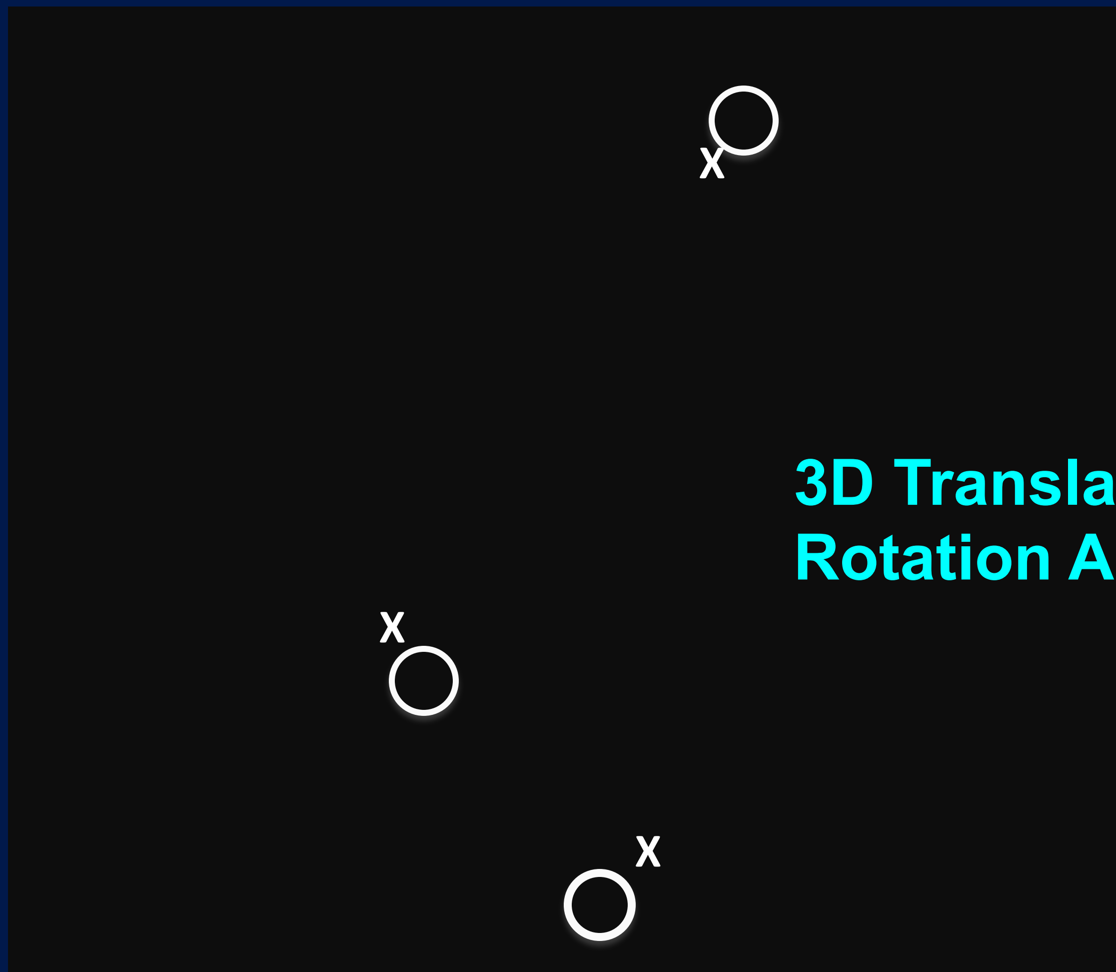


3D Translation Alignment

RMS = 1.5 mm

Markers are not always enough

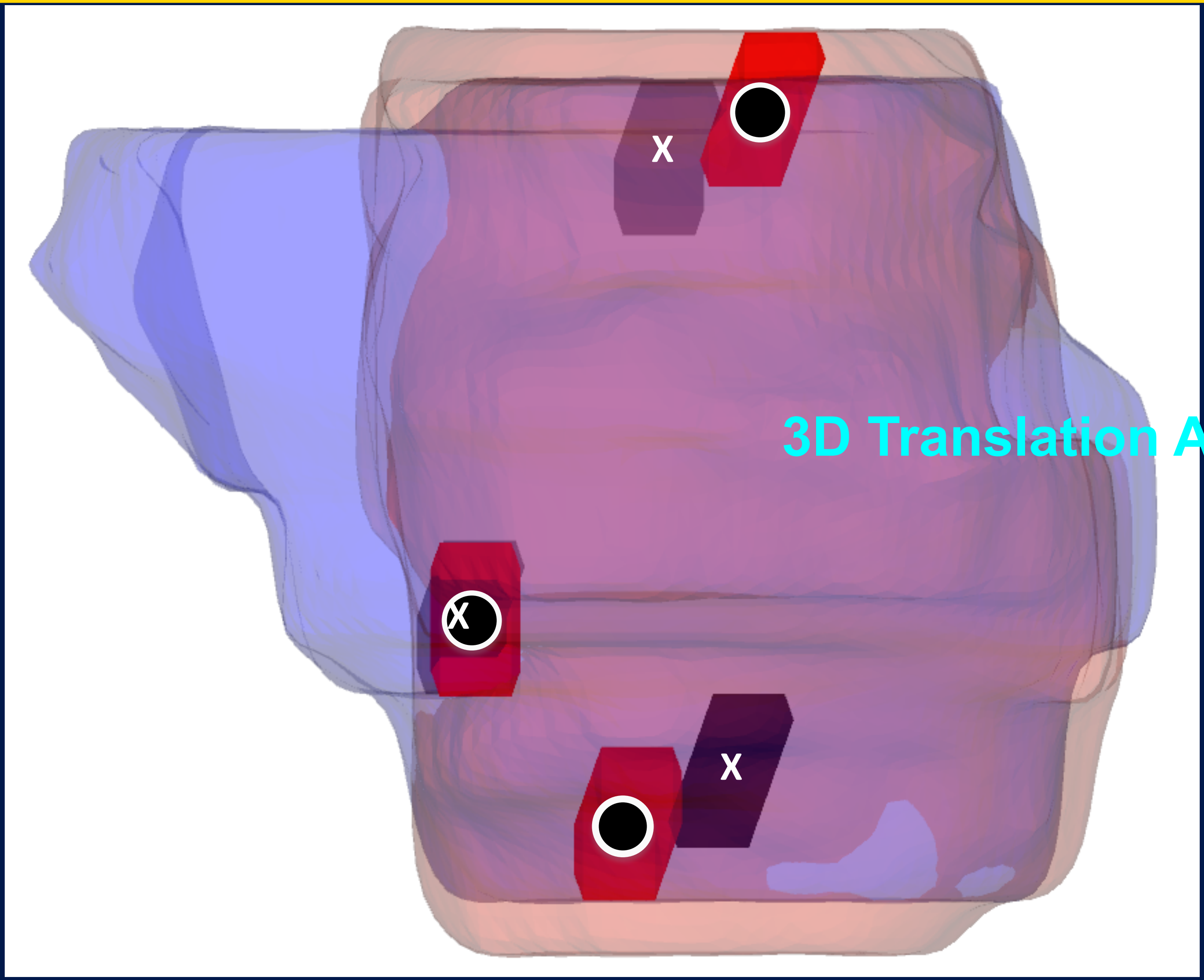
1 cm



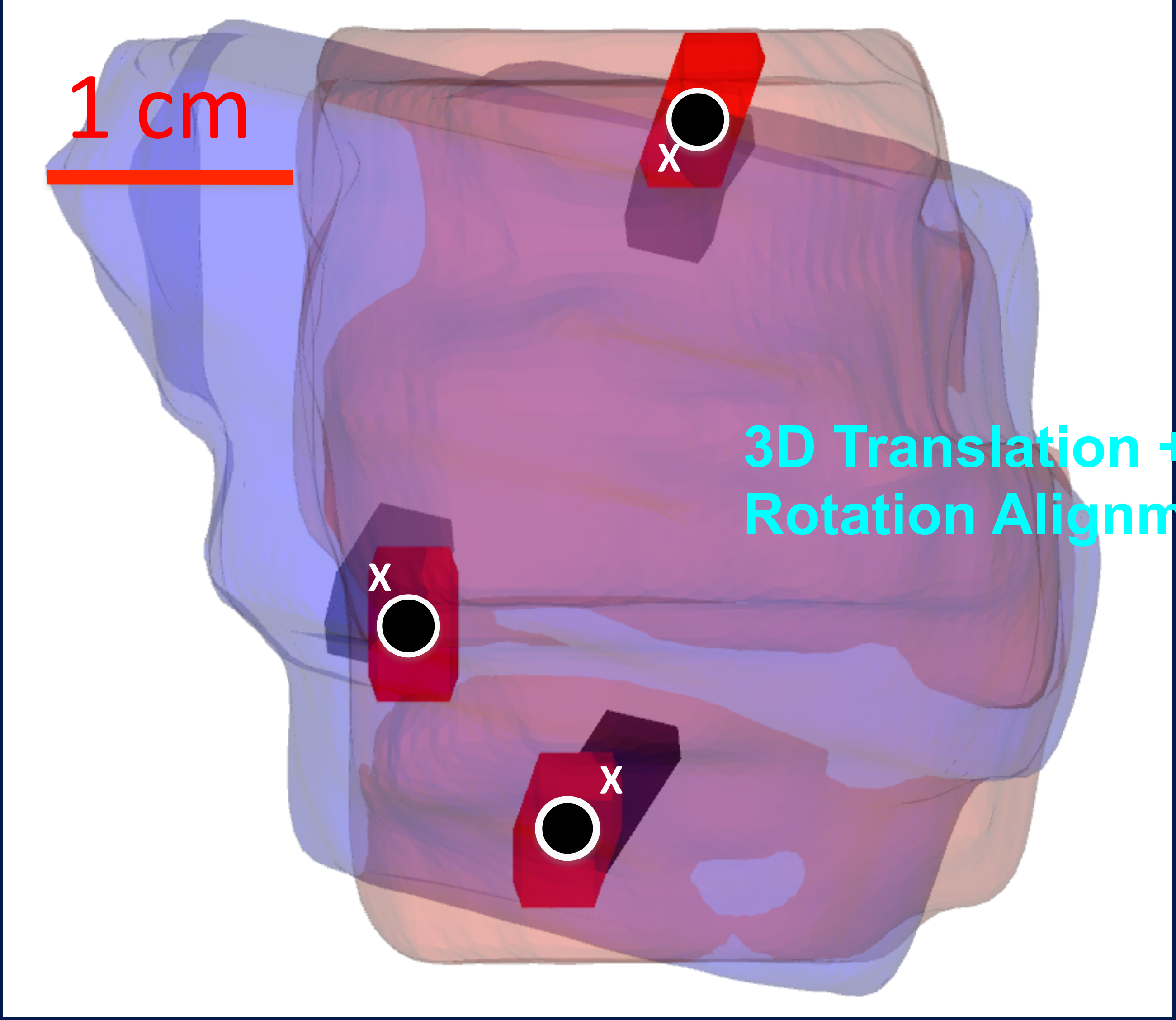
3D Translation + Rotation Alignment

RMS = 0.3 mm

Markers are not always enough



Markers are not always enough



In-Room Technologies: X-ray - based

<u>Varian</u>
kV planar
kV CBCT
MV planar

<u>Elekta</u>
kV planar
kV CBCT
MV planar

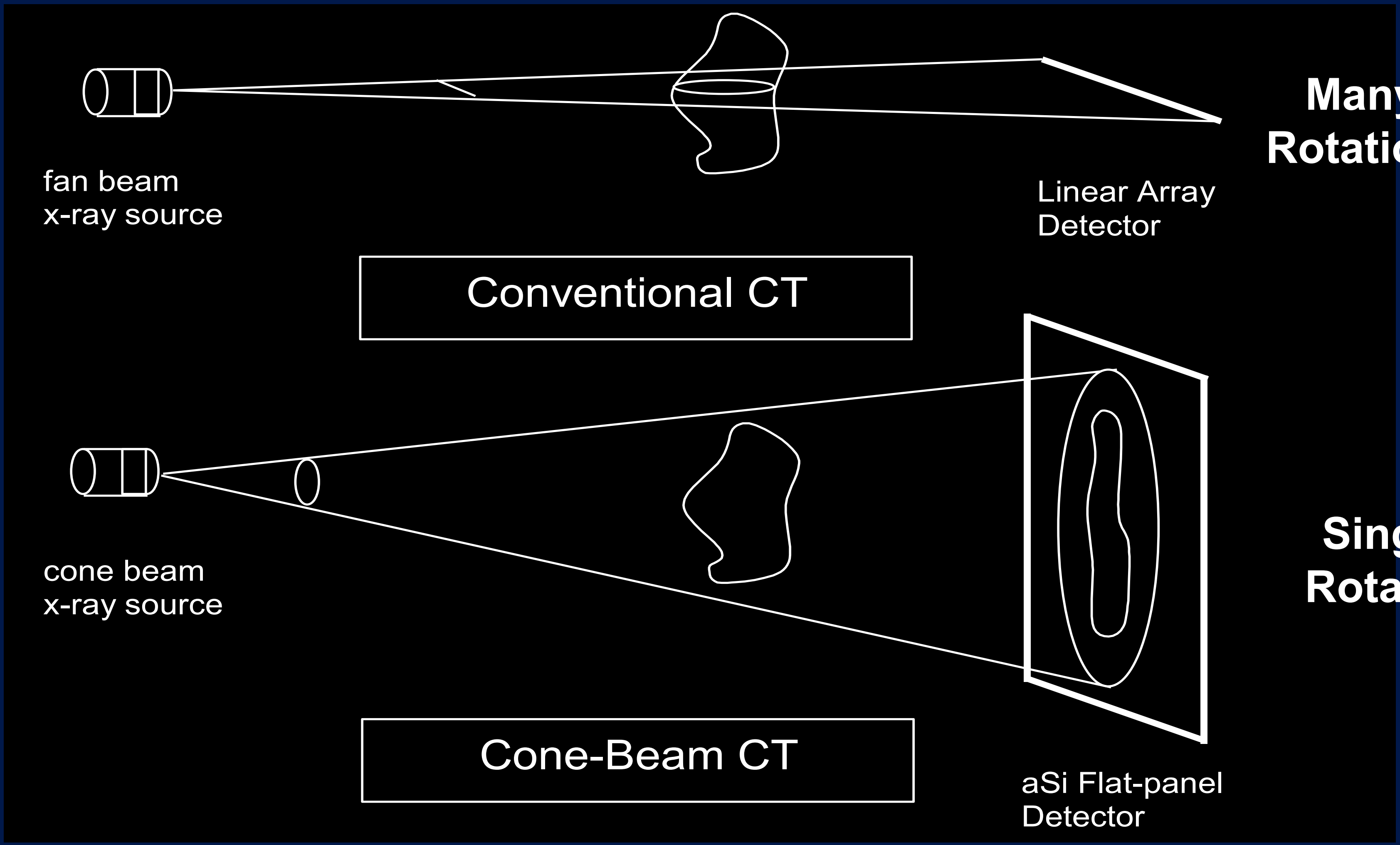
<u>Siemens</u>
MV planar
MV CBCT

<u>Accuracy Tomotherapy</u>
MV CT

<u>CyberKnife</u>
kV planar

<u>Siemens</u>
In-room CT

Cone-Beam CT: From Slice to Cone



Many Rotations

Single Rotation

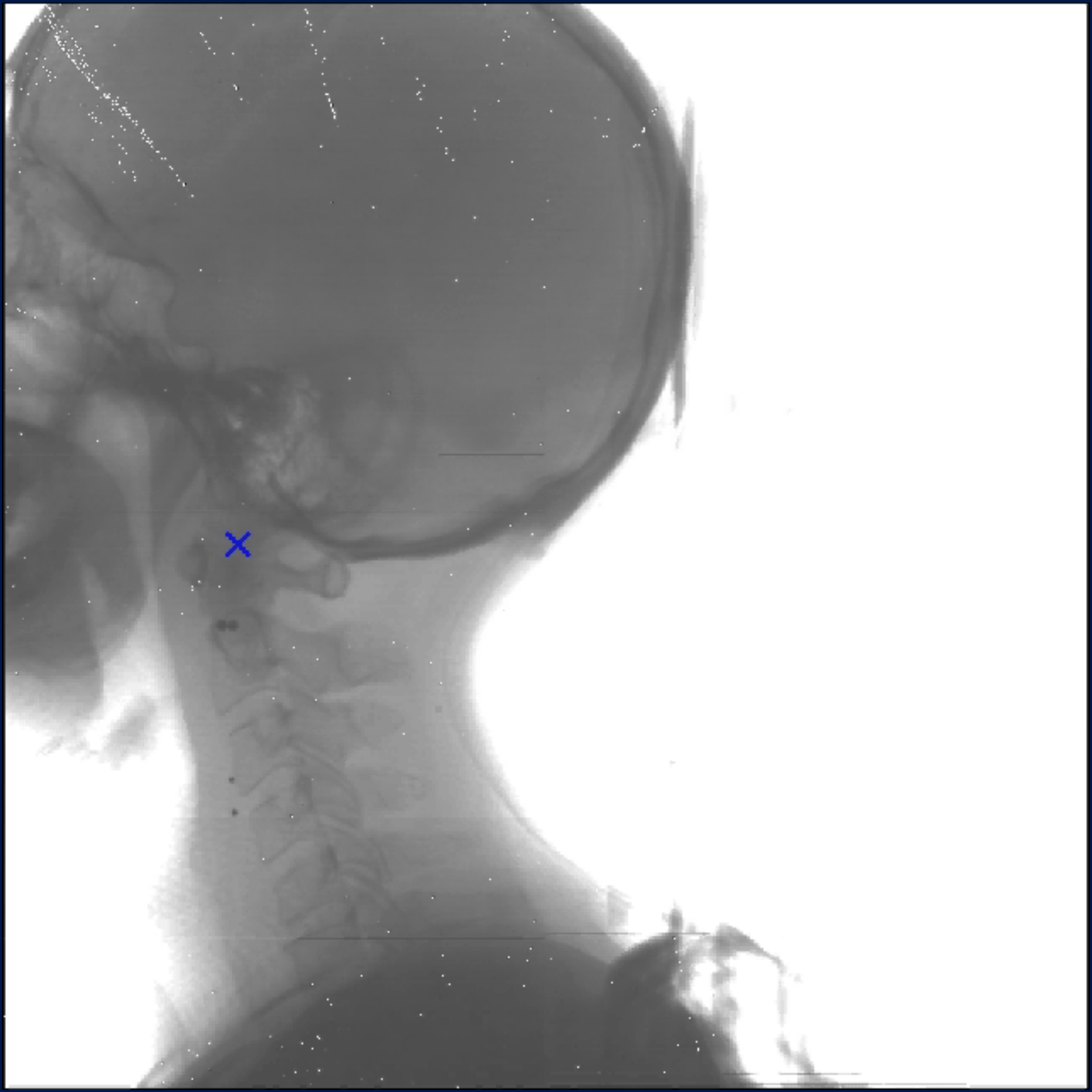
*Courtesy DA Jaffray, PMH

Flat-panel: Shortcomings Relative to CT Detectors

- Lower Efficiency - Lower x-ray cross-section
- Higher noise characteristics – additive noise from electronics
- Slower readout per frame (10-20 fps vs 100's of fps)
- Signal Memory from frame to frame – a.k.a. 'Lag' or 'Ghosting'

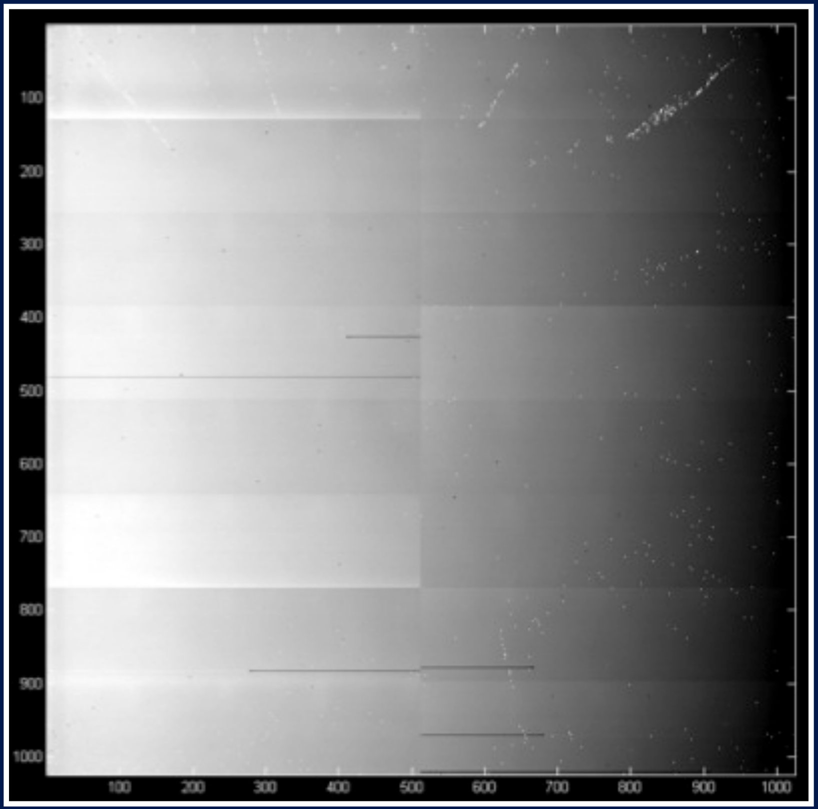
Raw Projection Data

- 1024x1024
- Defects
- Unequal exposure

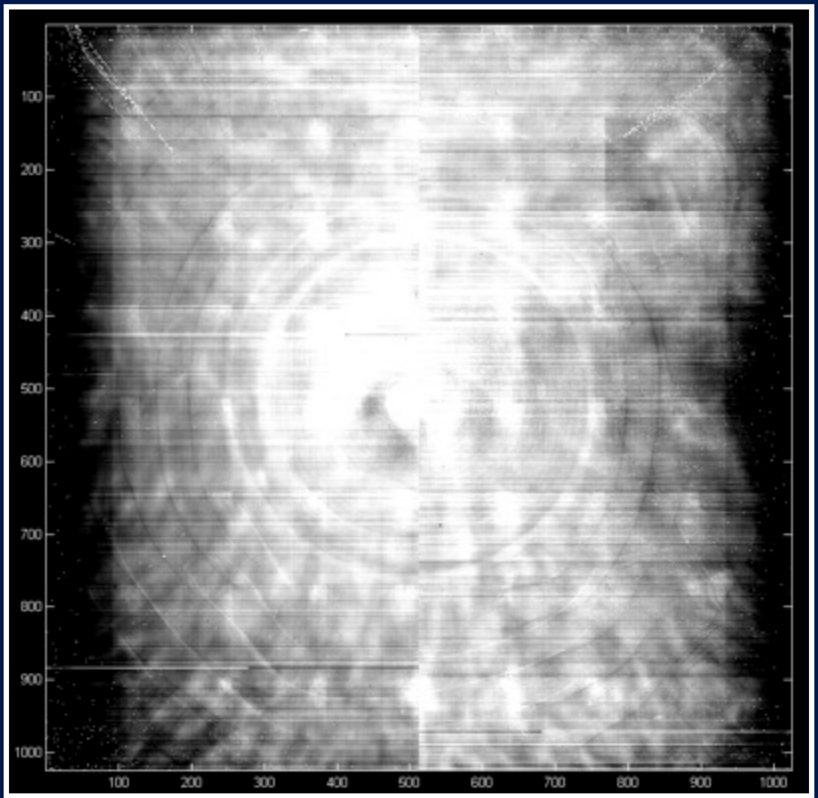


*Courtesy DA Jaffray, PMH

Dark/Flood (aka: Gain/Offset)



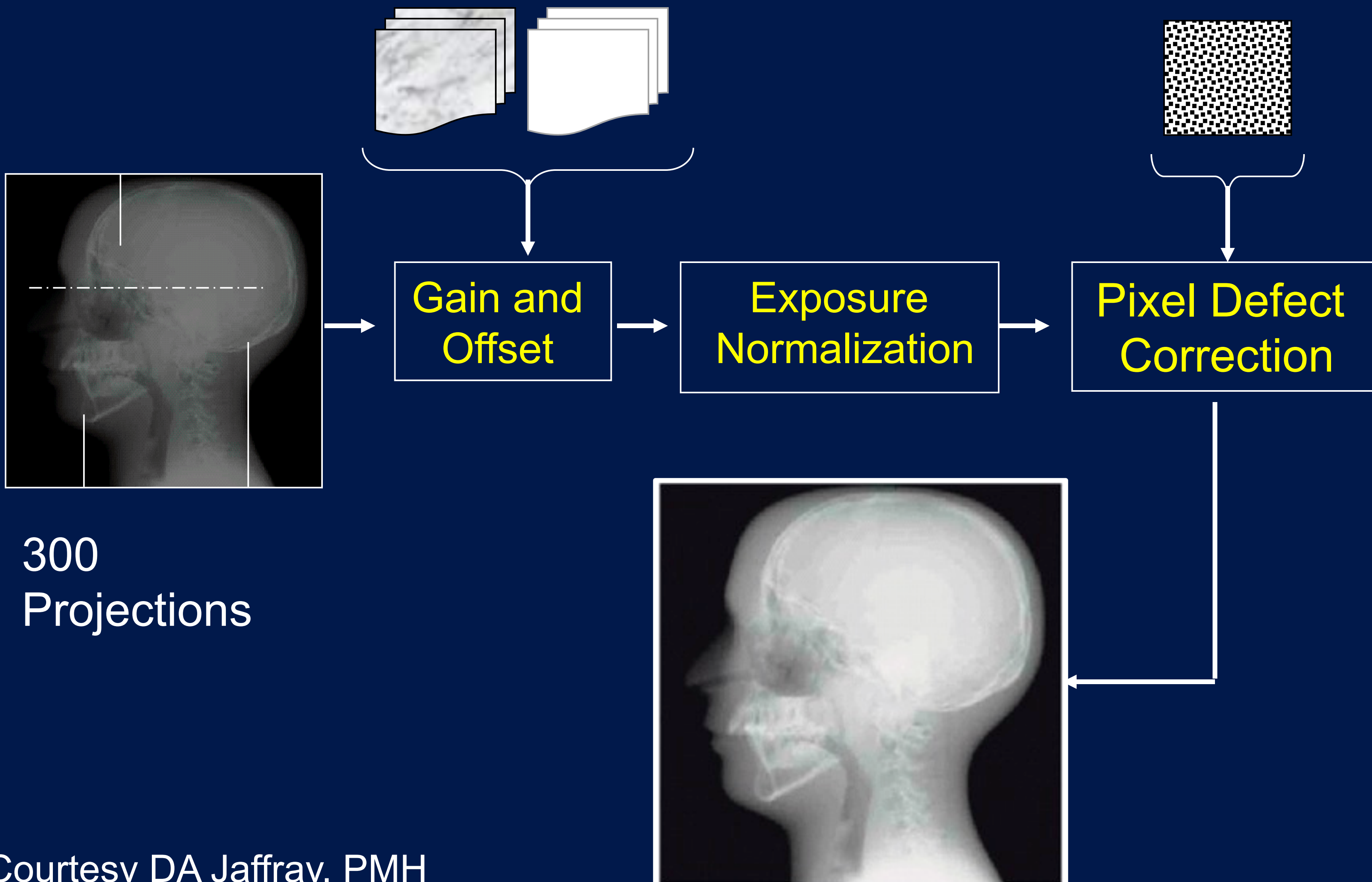
Flood Field



Dark Field

*Courtesy DA Jaffray, PMH

Processing of Projection Data



*Courtesy DA Jaffray, PMH

Processed Projections

- Flood/dark defect corrected
- Aperture / resample 4x4
  - time
  - space
  - noise
  - contrast

*Courtesy DA Jaffray, PMH

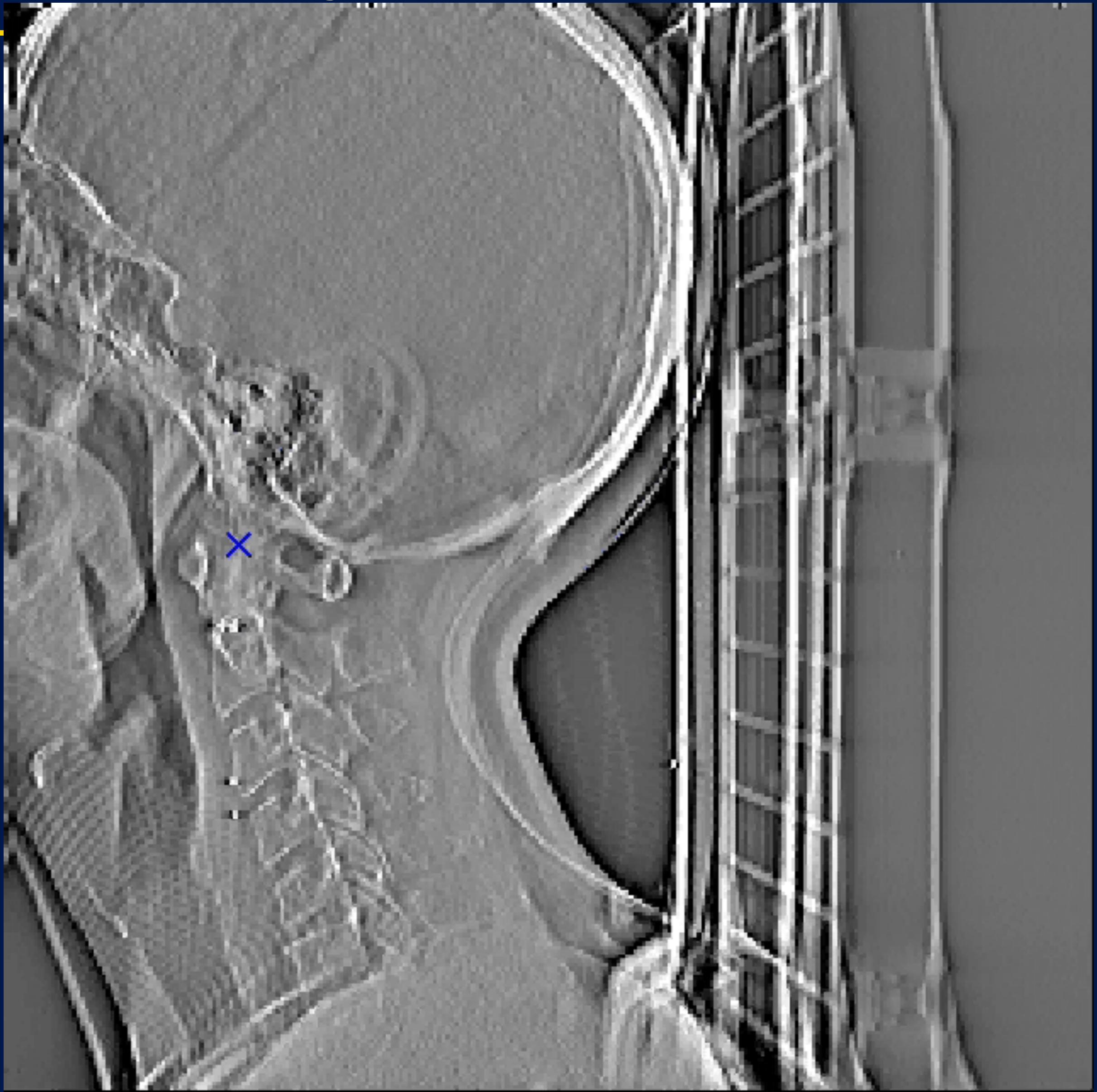
Processed Projections

- attenuation $= -\ln(I/I_0)$
- "white" bones

*Courtesy DA Jaffray, PMH

Processed Projections

- filtered
  - ramp + hamming=1
- Appears as edge enhancement

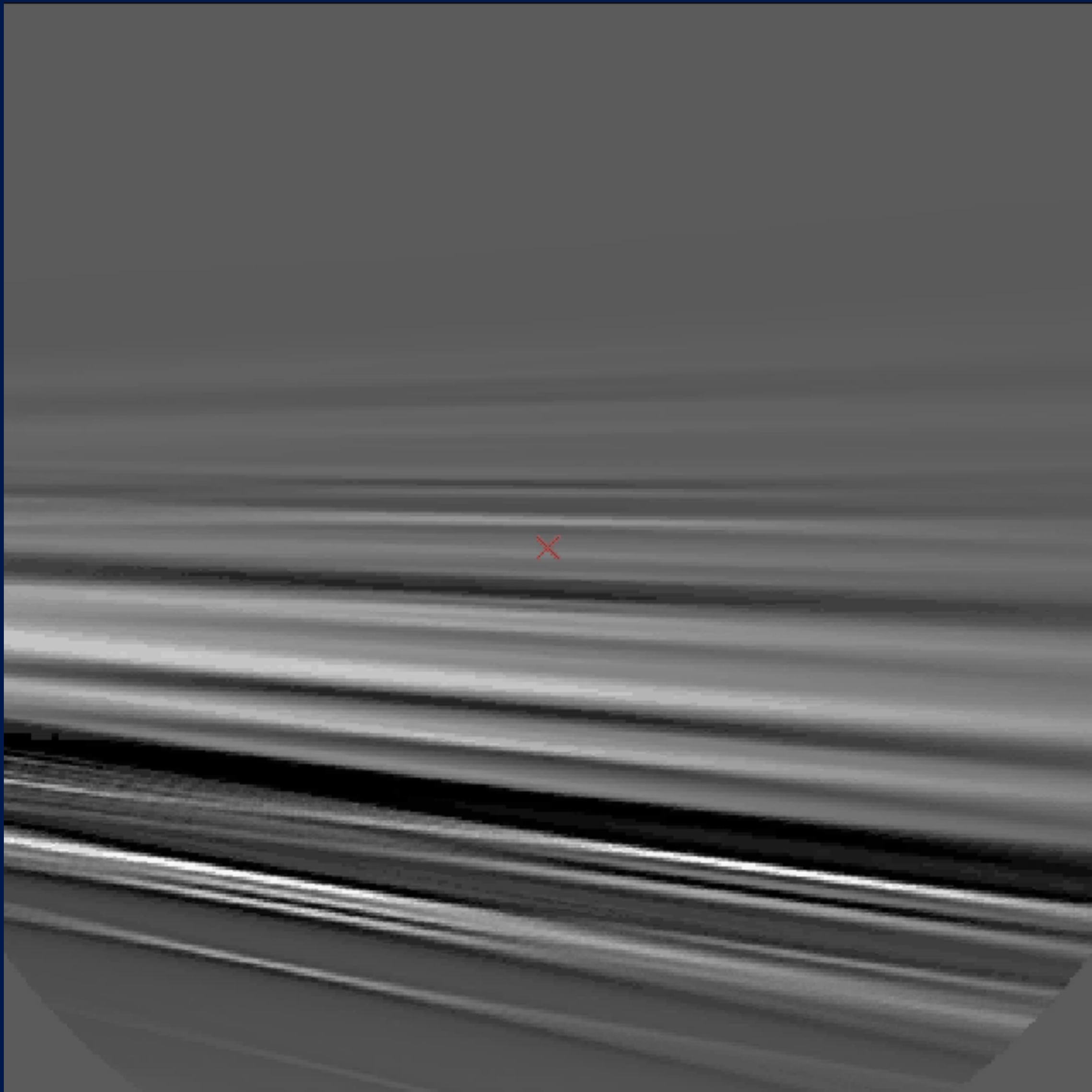


*Courtesy DA Jaffray, PMH

Axial Reconstruction

- 651 projections
- 360 deg
- 40cm x 40cm

$$\Delta s \cdot \sum_{i=1}^{N} \mu_i = -\ln I / I_0$$



*Courtesy DA Jaffray, PMH

Task Groups on QA for IGRT

We have lots (and lots, and lots)!

- TG-58 (Portal Imaging)
- TG-104 (Image-Guidance Systems)
- TG-142 (General Accelerator QA)
- TG-148 (Tomotherapy)
- TG-135 (Robotic Radiosurgery)
- TG-154 (Ultrasound)
- TG-179 (CT-based IGRT)

Quality Assurance Issues

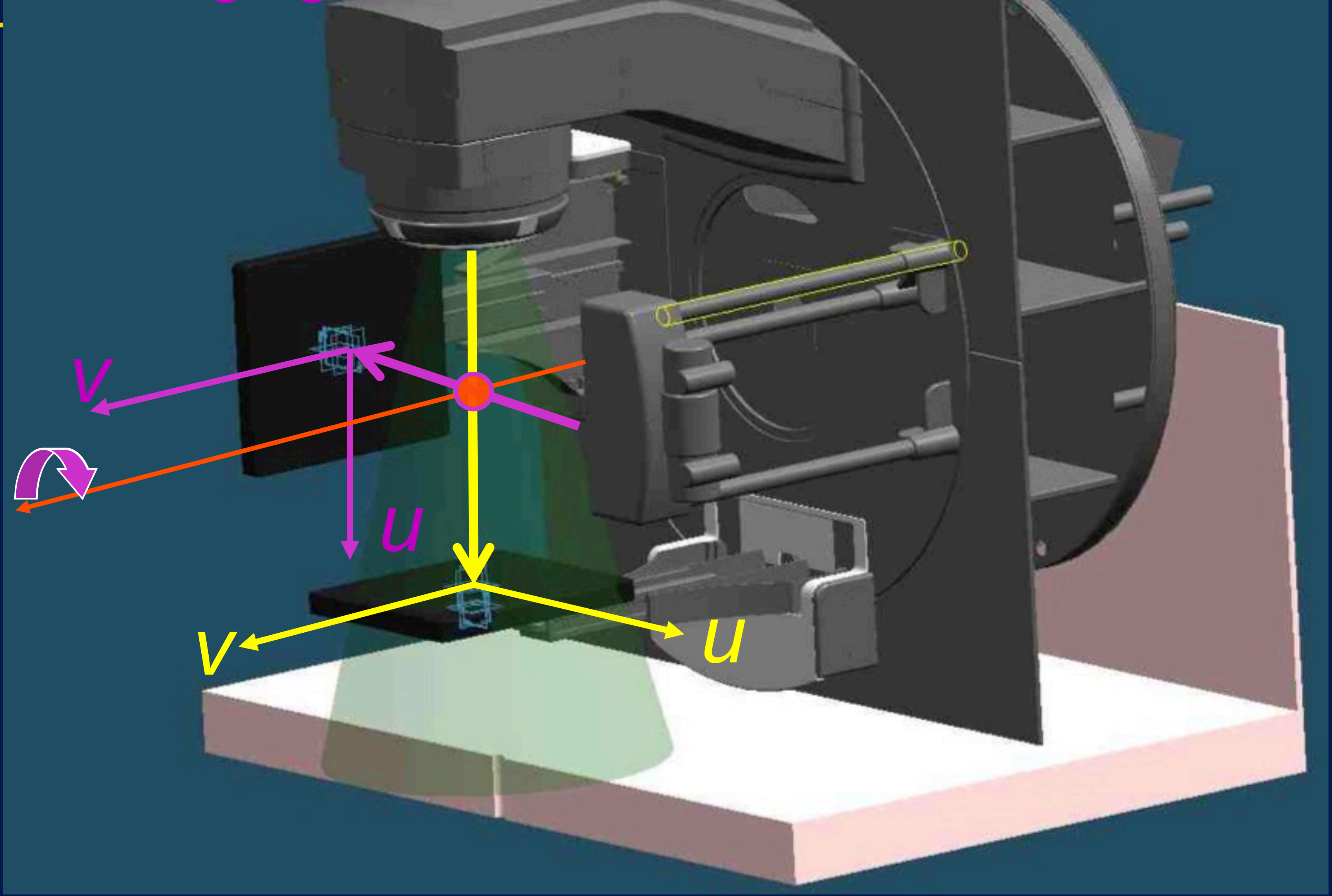
- Geometric Accuracy
- Image Quality
  - Scale and distance Accuracy
  - Low Contrast Resolution
  - Spatial Resolution
  - Uniformity and Noise
- Image Dose
- Accuracy of CT Numbers
- Image Registration
- Accuracy of Remote-Controlled Couch

Cone-Beam CT: Geometric Calibration

- kV/MV coincidence
- Stability
- Localization
  - guidance

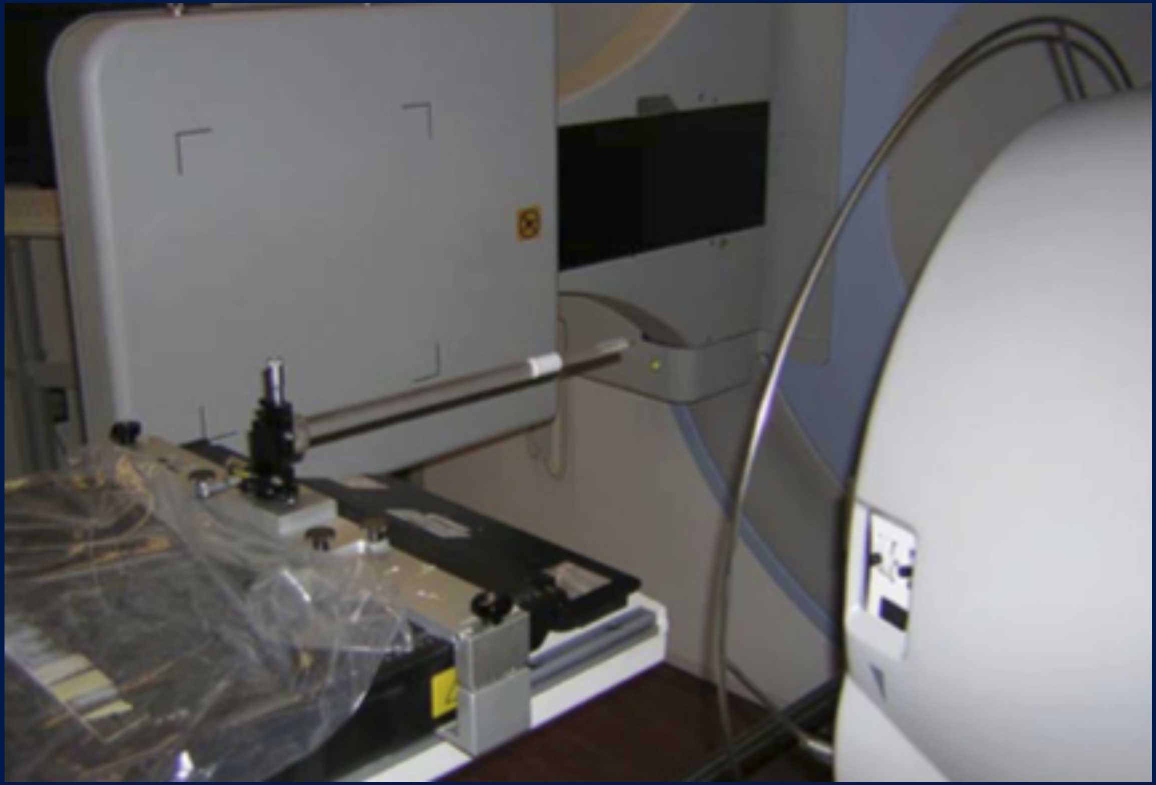
MV Radiation Isocenter

kV Imaging Isocenter

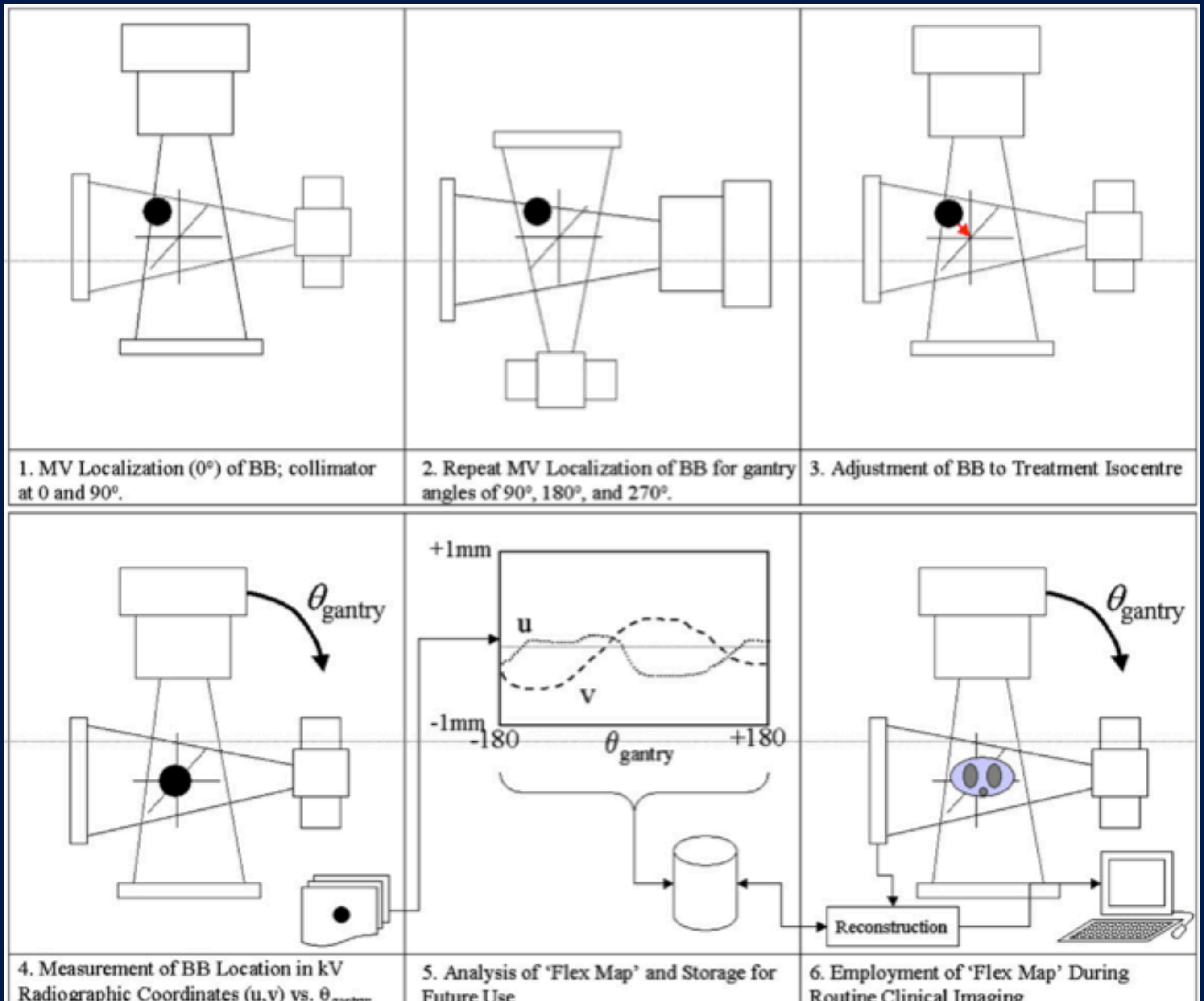


Bissonnette, et al, IJROBP 2008

Commissioning Isocenter

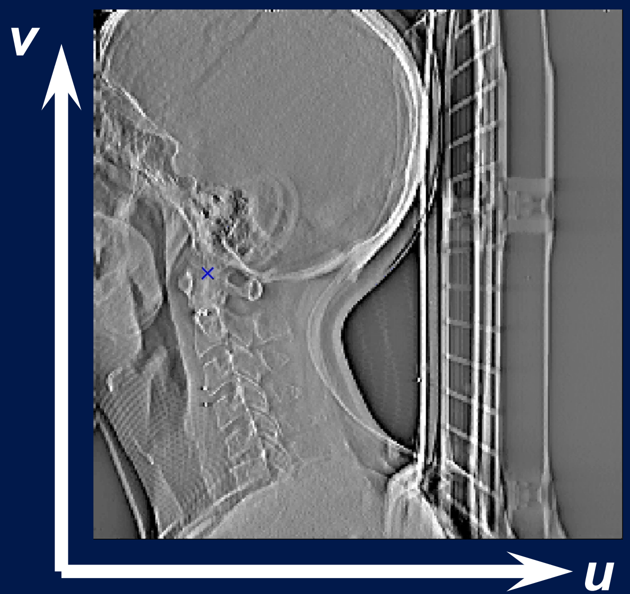


Commissioning Isocenter



Linking Projection and Reconstruction

Projection



Reconstruction

- 2-D
- Divergent
- Magnification
- Overlying structures

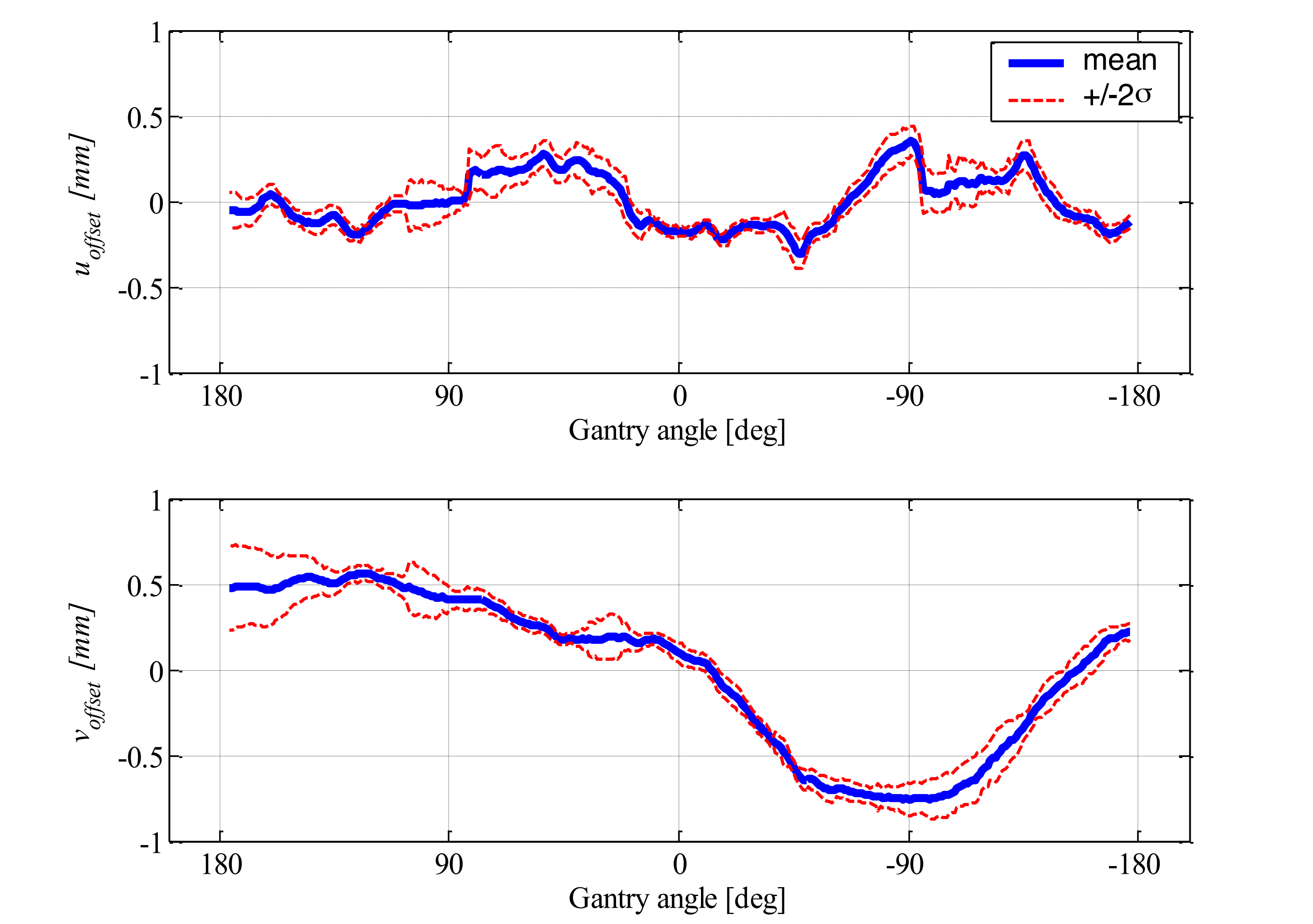
- 3-D
- Slices
- Precise geometry
- soft-tissue

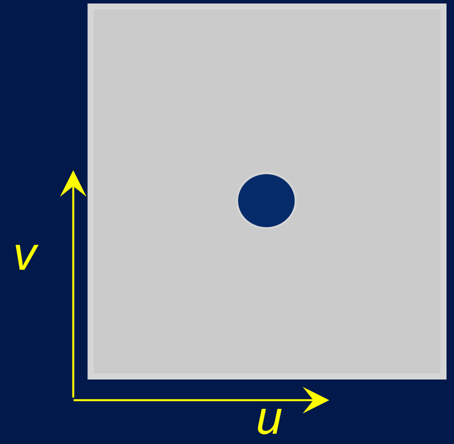
* Courtesy of J-P Bissonnette & DA Jaffray, Princess Margaret Hospital

Linking Projection and Reconstruction

* Courtesy of J-P Bissonnette & DA Jaffray, Princess Margaret Hospital

Long-Term Stability: FlexMap



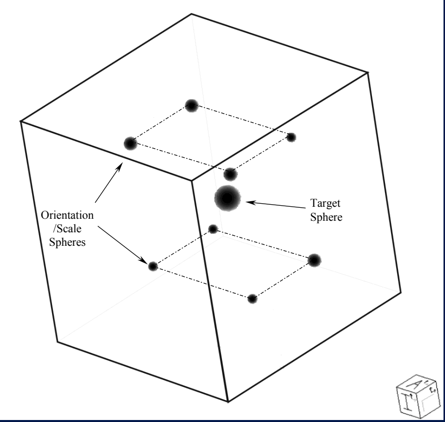


12 calibrations over 9 months

* Courtesy of J-P Bissonnette & DA Jaffray, Princess Margaret Hospital

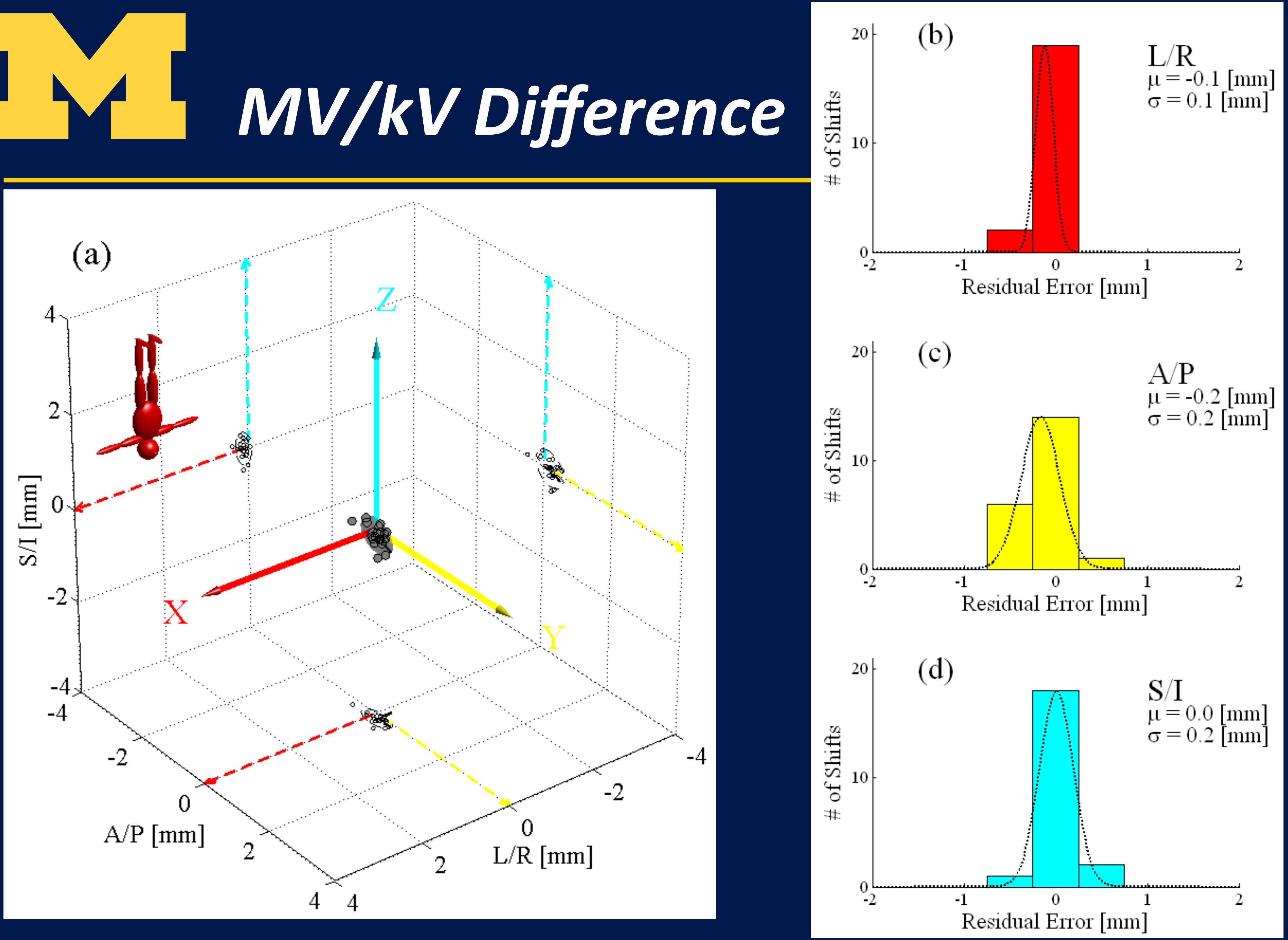
Targeting Study

- 21 sessions:
  - Over a 3 month period
  - Three different operators
  - Single calibration map
- Geometric calibration maps monitored weekly in parallel study.



* Courtesy of J-P Bissonnette & DA Jaffray, Princess Margaret Hospital

MV/kV Difference



* Courtesy of J-P Bissonnette & DA Jaffray, Princess Margaret Hospital

Commissioning Isocenter @ UM

- A test was performed to align the BB phantom with the gantry cross hairs
- Gantry 0 for the left-right alignment
- Gantry 270 for the superior-inferior and anterior-posterior alignment.
- The phantom was imaged using kV and MV systems at 4 cardinal angles.

Commissioning Isocenter @ UM

Source	Grat vs MV CAX Distance between	MV CAX vs BB Distance Between	kV CAX vs BB Dist Between
0	0.0 mm	0.2 mm	0.4 mm
90	0.0 mm	0.2 mm	0.2 mm
270	0.0 mm	0.5 mm	0.3 mm
180	0.0 mm	0.5 mm	0.3 mm

Deviation of the BB from isocenter for the four cardinal angles.

Application for MV-CBCT & MVCT

- MV CBCT – image aqusition uses the same beam as Tx
- MVCT – image acquisition also uses the same beam as Tx

Inherently Aligned!

Commissioning Image Quality - Planar

- Leeds phantom was used for the kV image evaluation
- Las Vegas phantom was used for the MV imaging evaluation.
- The phantoms were placed perpendicular to the table in the isocentric plane and perpendicular to the beam.
- The beam was placed in the lateral position (270 or 90 degrees).
- The procedures for standard monthly QA based on TG 142 were followed using the presets defined.

http://www.leedstestobjects.com

Leeds Phantom

- Sensitometric measurements
  - 10 test point details, 5.6mm diameter
- Resolution limit
  - 0.5 to 14.3 LP/mm
- Low-contrast large-detail detectability
  - 17 details, 11mm diameter
- High-contrast small-detail detectability
  - 17 details, 0.5mm diameter

Las Vegas Phantom

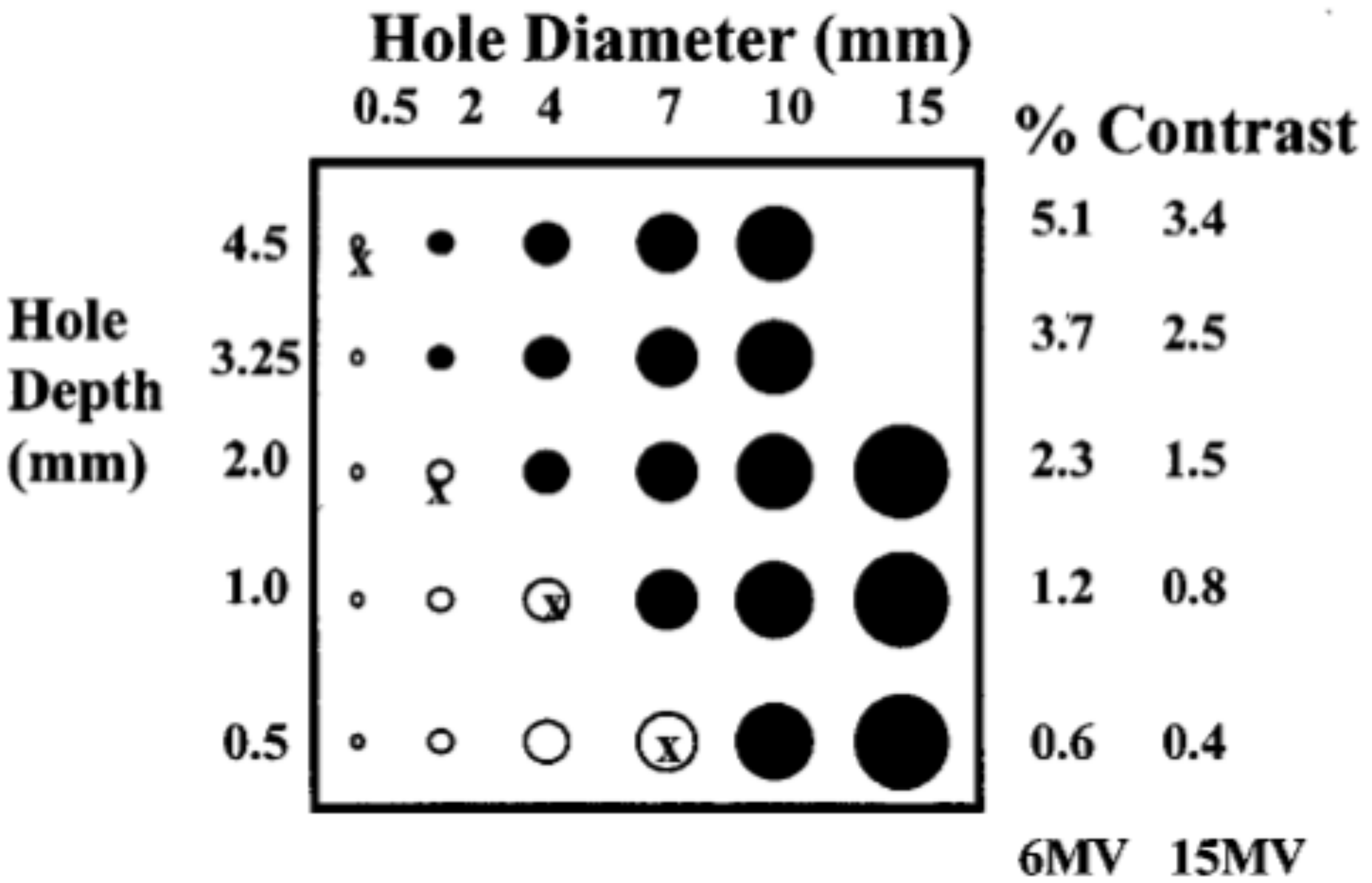


FIG. 10. Aluminum Las Vegas phantom for EPID image contrast and spatial resolution.

Commissioning Image Quality - Planar

3 Imager Alignment and Quality

(2 mm, Baseline)

		MV		kV	
Ref. Image Centered?		Meets Baseline	Baseline	Meets Baseline	Baseline
Ref. Image Quality		Meets Baseline		Meets Baseline	
Reference Distance	X	140.7	140.0	149.2	150.0
	Y	140.3	140.0	149.4	150.0
Spatial Resolution		5.0 holes	5.0	11.0 holes	10.0
Contrast		4.0 holes	5.0	18.0 holes	18.0
Uniformity		0.4 %	0.5	0.2 %	0.4

Image quality, spatial resolution, contrast, and uniformity

Commissioning Image Quality - Volumetric

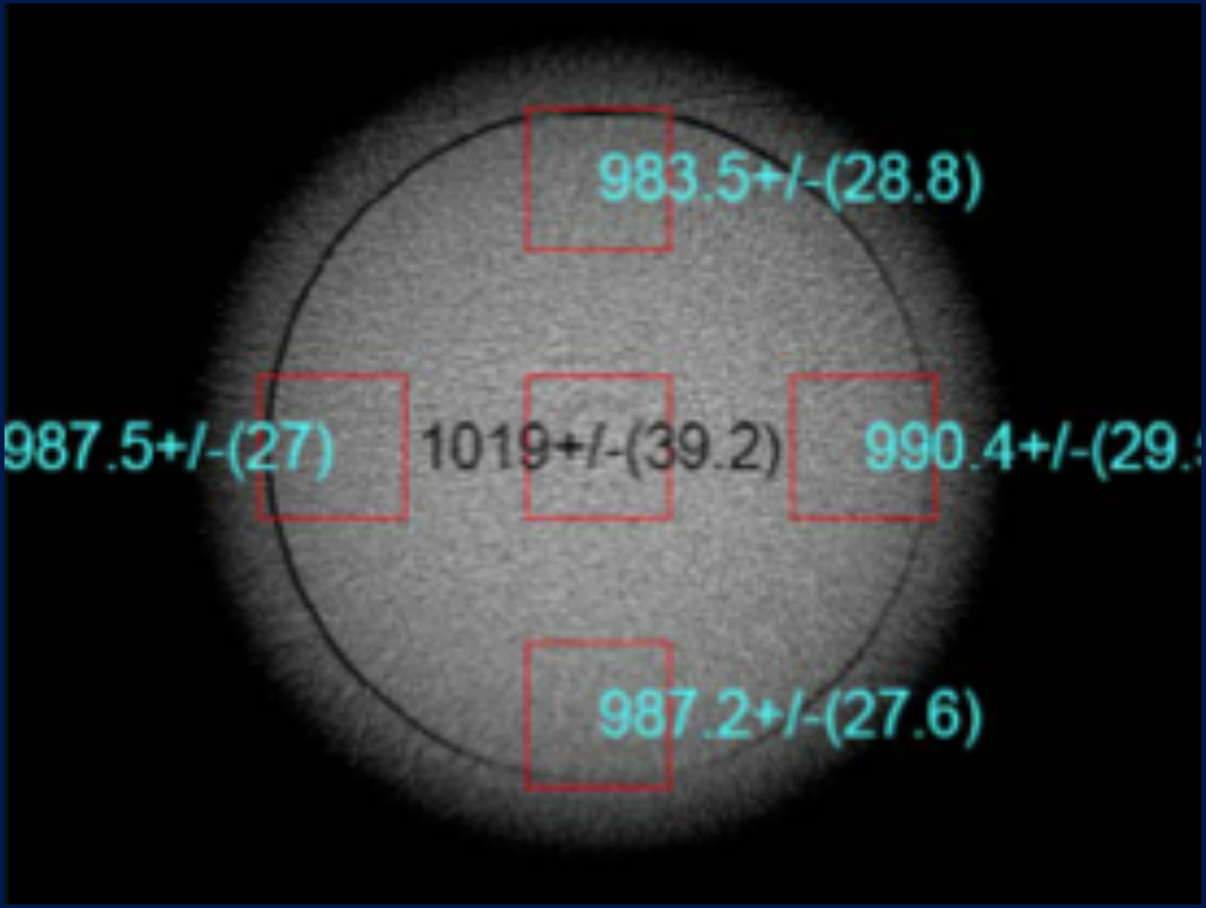
- Catphan phantom: kV CBCT image evaluation.
- Phantom was placed at the room isocenter using the lasers.
- CBCT image was acquired using the High Quality Head technique.
- Reference distance: measuring the dimension of a known phantom.
- HU constancy: circular regions of interest in offline review of the imaged rods of known density.

Commissioning Image Quality - Volumetric

- Uniformity: measuring a square region of homogeneous image intensity in the specified region of the phantom.
- Spatial resolution: evaluating the number of visible patterns discernable on the phantom image.
- Contrast resolution: evaluating the visibility of known contrast rods in the CBCT image.

Bissonnette, et al, Med Phys 2008

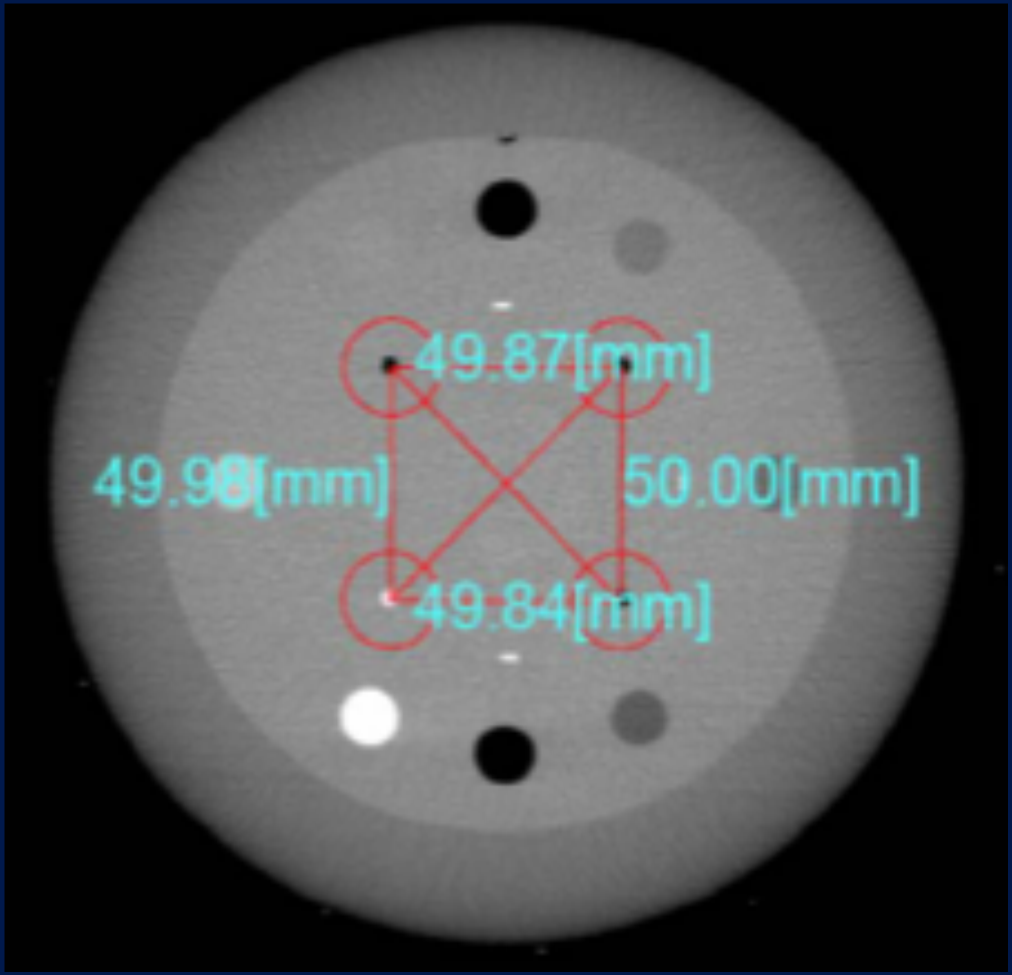
Slice through CatPhan Phantom



Uniformity

Bissonnette, et al, Med Phys 2008

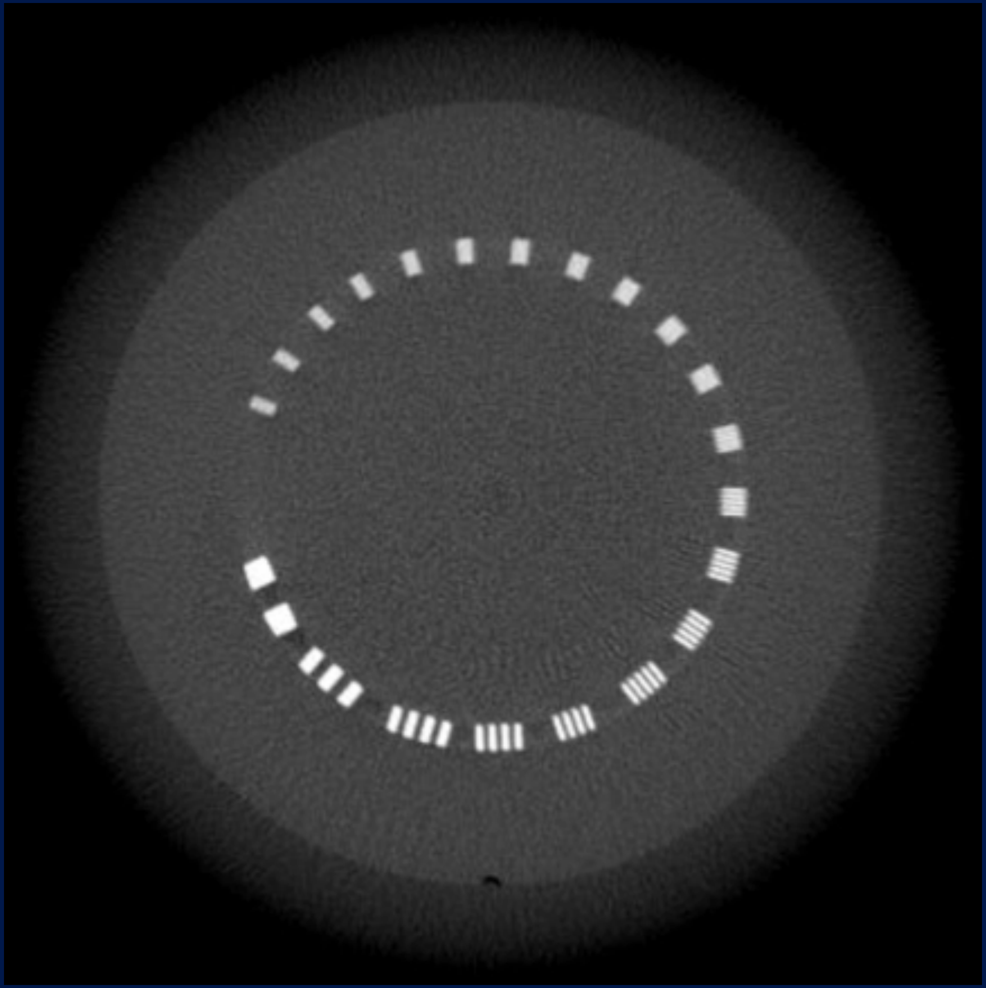
Slice through CatPhan Phantom



Reference Distances: Scale

Bissonnette, et al, Med Phys 2008

Slice through CatPhan Phantom



Spatial Resolution

Spatial Resolution Comparison

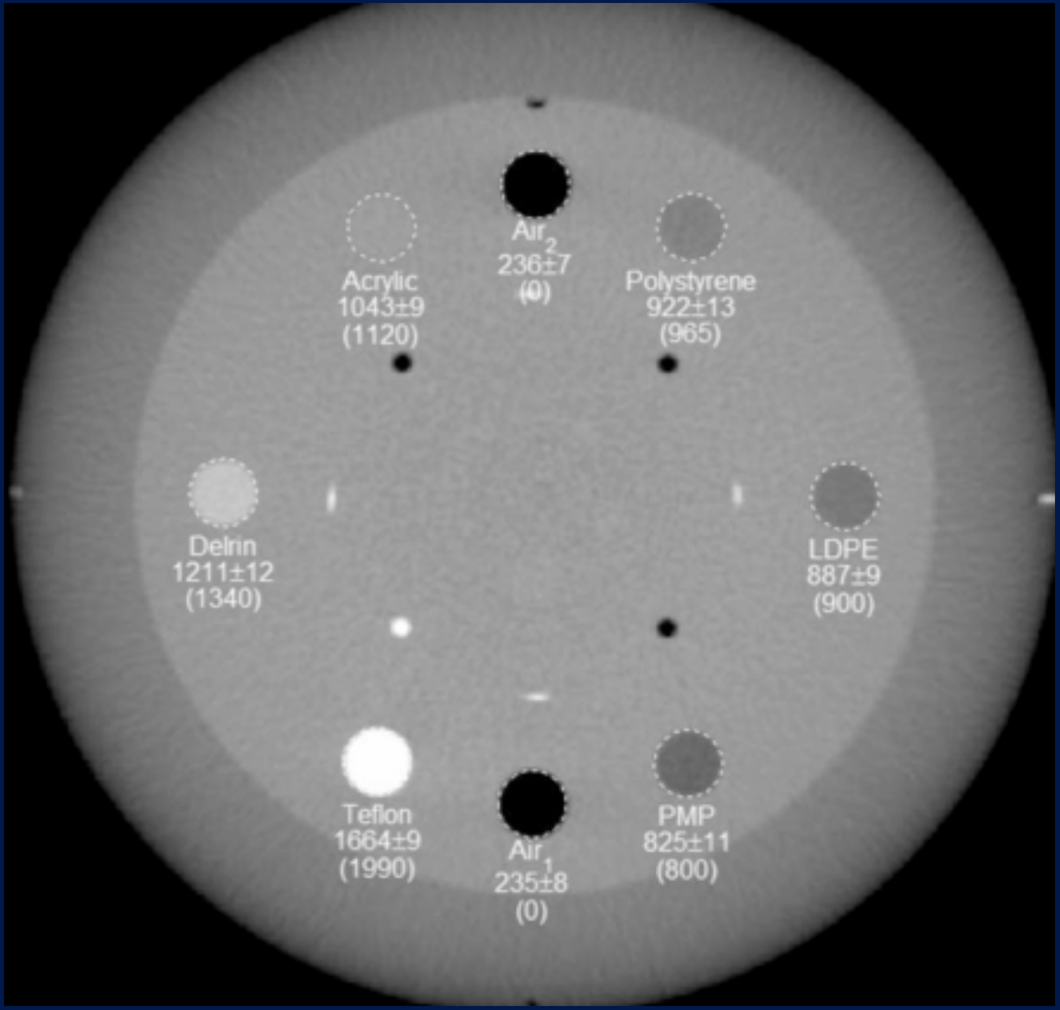
- 6–9 line-pairs/cm for kV-CBCT
  - S Yoo, et al, Med Phys 2006
- 4 line-pairs/cm for MV-CBCT
  - O Gayou, et al, Med Phys 2007
- Enables visualization of high-contrast objects of 1–2.5 mm in size.
- MVCT images, the vendor's specification indicates that a 1.6 mm high contrast object should be resolved
  - K Langen, TG 148, Med Phys 2010

Spatial Resolution Comparison

- Spatial resolution has been shown to be independent of dose or location of the phantom with respect to the isocenter plane
  - JP Bissonnette et al, Med Phys, 2008

Bissonnette, et al, Med Phys 2008

Slice through CatPhan Phantom



HU Constancy

Low Contrast Comparison

- kV-CBCT: 1% contrast objects, 7 mm in diameter
  - S. Yoo, et al, Med Phys 2006
- MVCT: resolve 13 mm diameter objects with 2% density differences from background
  - SL Meeks, et al, Med Phys 2005
- MV-CBCT: resolve 2 cm objects with 1% contrast
  - O Gayou et al, Med Phys 2007

Commissioning Image Quality – Volumetric @ UM

Ref. Image Quality		Meets Baseline	Baseline
Reference Distance	X	49.9	50.0
	Y	49.9	50.0

	Material	Measured CT #	Baseline CT#
HU Constancy	Air	-999.0	-1000.0
	Acrylic	139.0	120.0
	LDPE	-101.0	-100.0
	Water	20.0	0.0
	Location	Measured CT #	Baseline CT#
Uniformity	Top	39.0	20.0
	Bottom	46.0	20.0
	Left	36.0	20.0
	Right	39.0	20.0

Spatial Resolution	
Measured Res.	Baseline Res.
9 pattern	9 patterns

Constrast Resolution	
Measured Contrast	Baseline Contrast
0.01 0	0.01
Contrast Res.	Baseline Cont. Res.
7 rods	5 rods

Image quality, HU constancy, uniformity, spatial resolution, and contrast resolution

Commissioning Image Registration and Correction @ UM

- The Iso Cube phantom was placed at the room isocenter determined by the lasers alignment to the Iso Cube central cross-hairs.
- CBCT acquired
- Alignment was performed and then an alignment was performed to the offset marker within the phantom.
- Shift was automatically applied to the table.
- Phantom was then visually inspected to evaluate the alignment of the lasers to the offset markers on the phantom

Commissioning Image Registration and Correction @ UM

Results:

- The lasers were within 0.5 mm of the offset markers on the phantom.
- For the re-test with image evaluation, the marker was within 1 mm of the image isocenter.
- The applied couch offset and the measured offset deviated by less than 1 mm for all tests. When the correction was applied to the couch and the second image was obtained, the central marker was within 1 mm.

Summary of QC tests recommended for CT-based IGRT systems – TG 179

TABLE II. Summary of QC tests recommended for CT-based IGRT systems. Tolerances may change according to expectations, experience and performance.

Frequency	Quality metric	Quality check	Tolerance
Daily	Safety	Collision and other interlocks	Functional
		Warning lights	Functional
	System operation and accuracy	Laser/image/treatment isocentre coincidence OR	± 2 mm
		Phantom localization and repositioning with couch shift	± 2 mm
Monthly or upon upgrade	Geometric	Geometric calibration maps[a] OR	Replace/refresh
		kV/MV/laser alignment	± 1 mm
		Couch shifts: accuracy of motions	± 1 mm
	Image quality	Scale, distance, and orientation accuracy[a]	Baseline
		Uniformity, noise[a]	Baseline
		High contrast spatial resolution[a]	≤ 2 mm (or ≤ 5 lp/cm)
		Low contrast detectability[a]	Baseline
If used for dose calculation	Image quality	CT number accuracy and stability[a]	Baseline
Annual	Dose	Imaging dose	Baseline
	Imaging system performance	X-ray generator performance (kV systems only): tube potential, mA, ms accuracy, and linearity	Baseline
	Geometric	Anteroposterior, mediolateral, and craniocaudal orientations are maintained (upon upgrade from CT to IGRT system)	Accurate
	System operation	Long and short term planning of resources (disk space, manpower, etc.)	Support clinical use and current imaging policies and procedures

[a]These tests can be performed on a semiannual basis after stability has been demonstrated, 6–12 months after commissioning.

Can we Calculate Dose on CBCT?

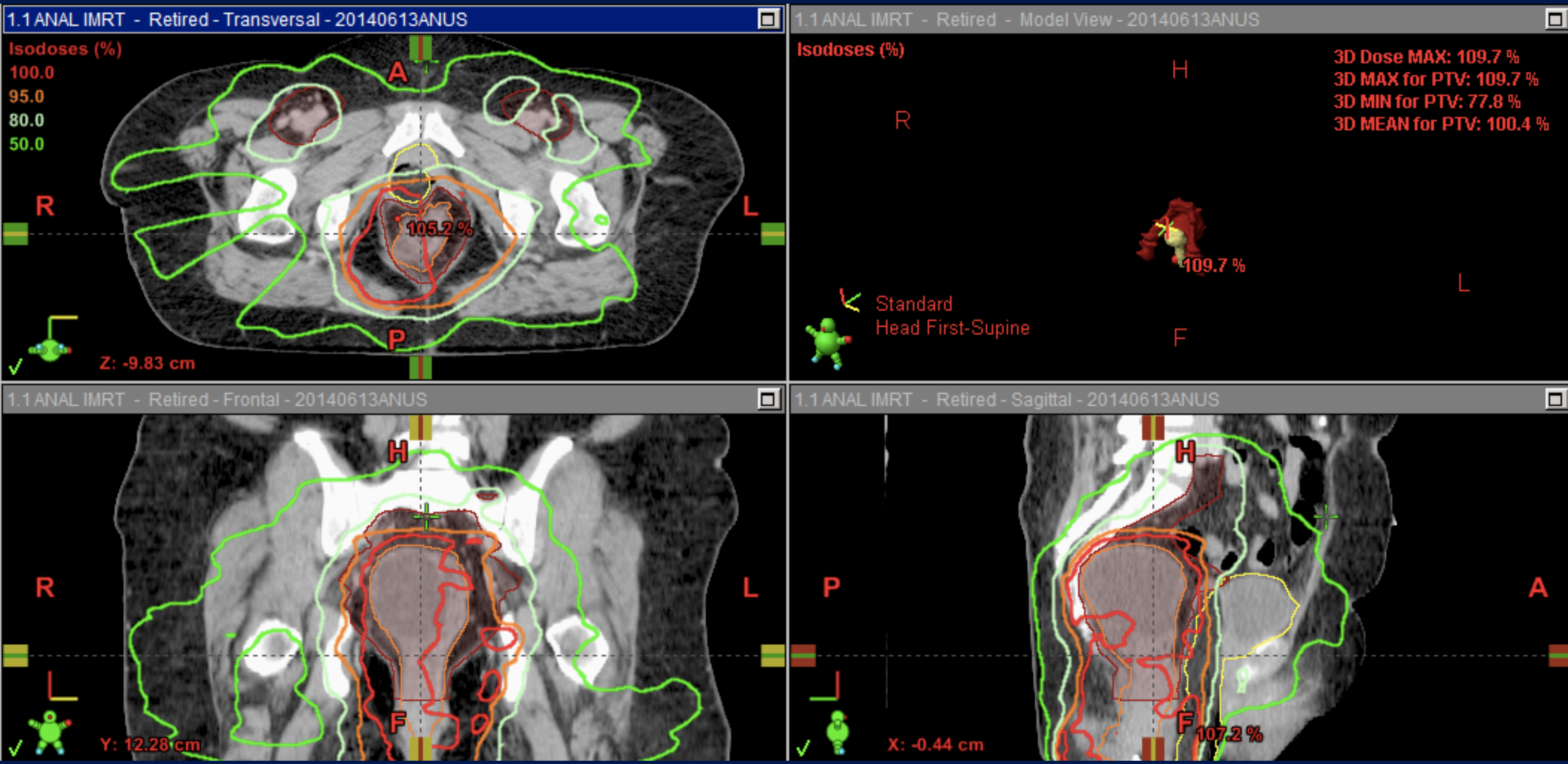
- Comparison of CT number on H&N CBCT scan using phantom

	HU on CBCT	Reference	% Error
Air	-1000	-1000	0.0%
Teflon	995	990	0.5%
Delrin	338	340	-0.6%
Acrylic	115	120	-4.2%
Air (bottom)	-1000	-1000	0.0%
Polystyrene	-45	-35	28.6%
LDPE	-105	-100	5.0%
PMP	-200	-200	0.0%

Can we Calculate Dose on CBCT?

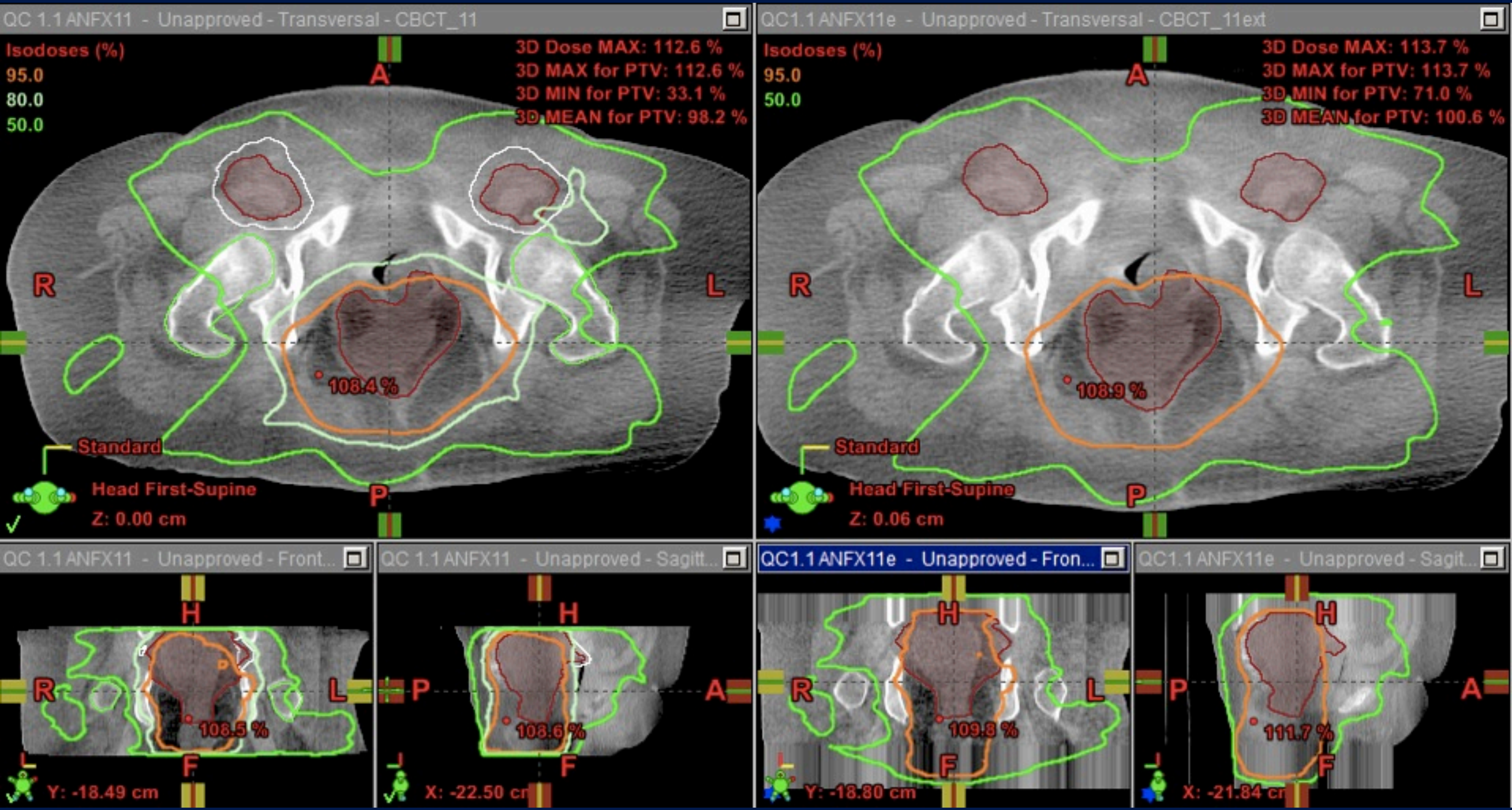
- Limited FOV can impact the dose calculation at the superior/inferior boundaries (due to lack of tissue and resulting electron scatter), therefore care must be taken when evaluating minimum or mean dose in these areas

Limitations of CBCT Dose Calculations

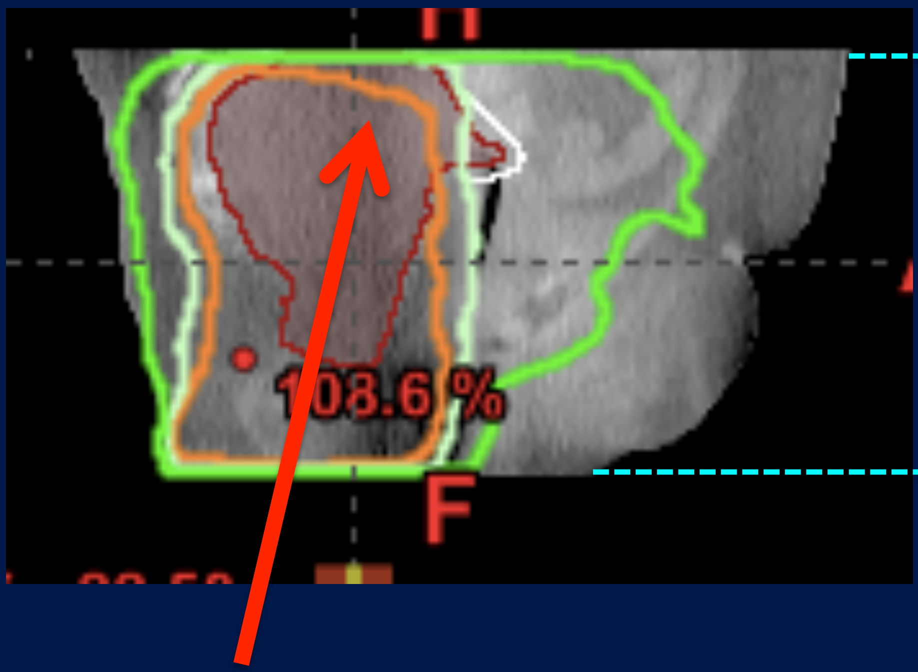


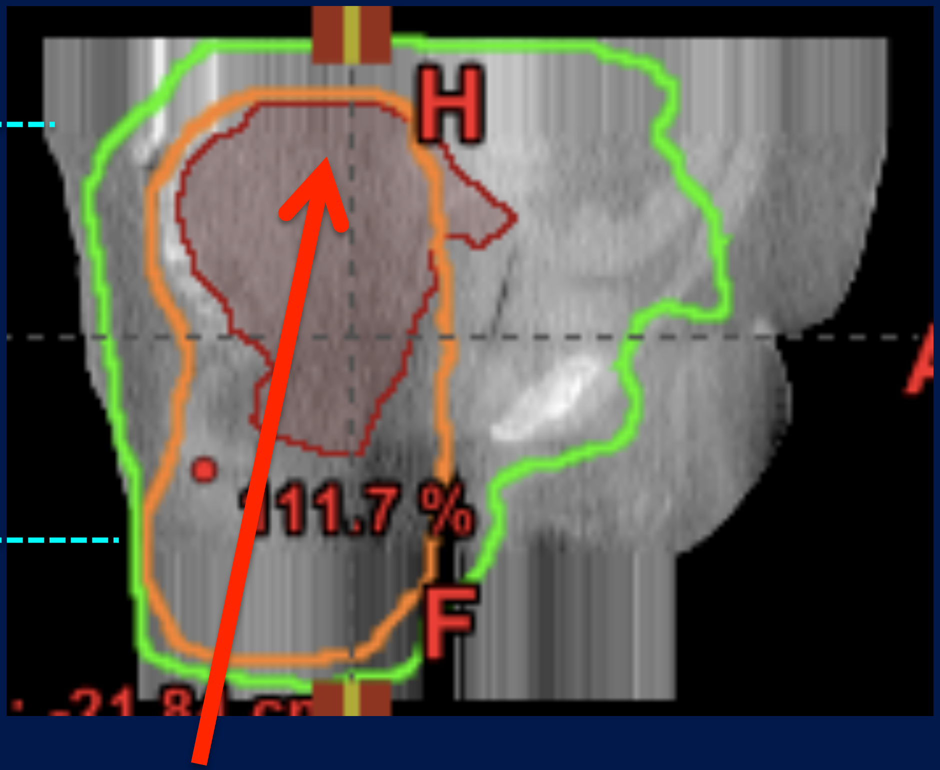
Limitations of CBCT Dose Calculations

Limitations of CBCT Dose Calculations



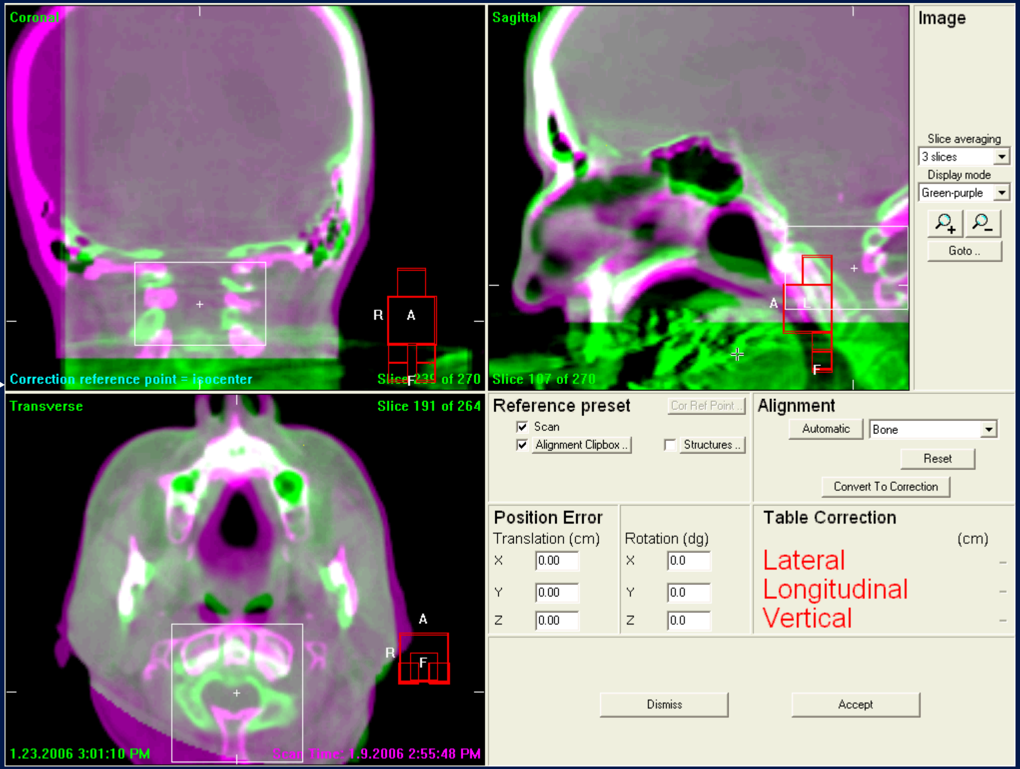
Limitations of CBCT Dose Calculations





So now you have a calibrated system…

- What are you going to do with it?

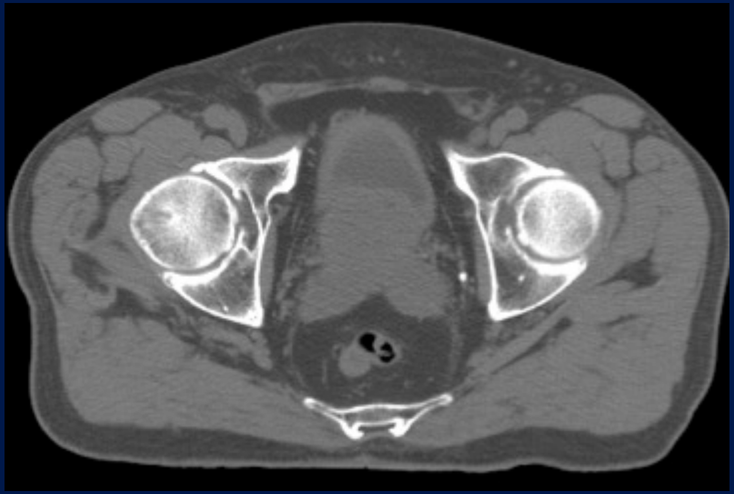


Quickly dispel myths…

- You can’t see anything on a CBCT!

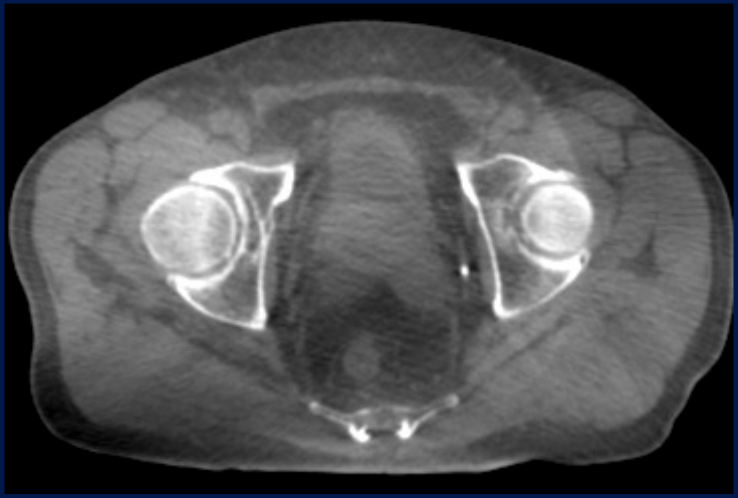
CBCT - Soft Tissue Visualization

Helical CT



Cone-beam CT

With non-linearity/
scatter corrections



*DA Jaffray, PMH

Quickly dispel myths…

- You can’t see anything on a CBCT!
- It’s too much dose!!

Summary

Doses from image-guided procedures

MV imaging:

- EPID: 4 - 6 cGy from two orthogonal portal images
- MVCT (TOMO): 1 - 3 cGy
- MV-CBCT: 1 - 16 cGy

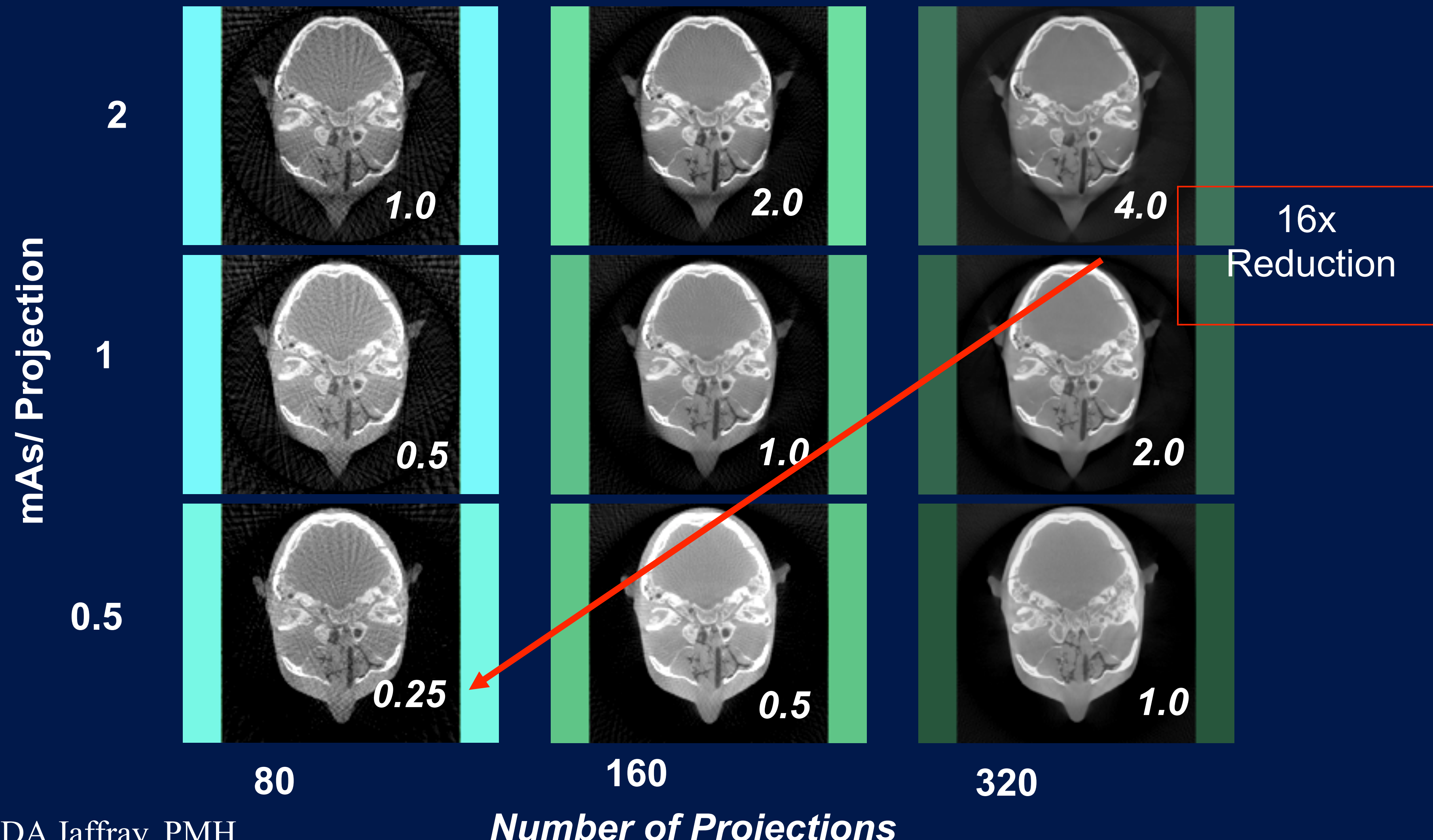
kV imaging:

- kV DR: 0.1 - 1.0 cGy
- kV-CBCT
  - Soft tissue: 0.1 - 3 cGy /acquisition
  - Bone: 0.3 - 6 cGy /acquisition

AAPM Annual Meeting 2012, Presented by: George Ding, Vanderbilt University
*Several references available

Deciding Upon the Necessary Image Quality for the Application

Variation of image quality with lens dose (cGy)



*DA Jaffray, PMH

Quickly dispel myths…

- You can’t see anything on a CBCT!
- It’s too much dose!!
- It takes waaaaaaaay to long!!!

How long does it take? An analysis of volumetric image assessment time

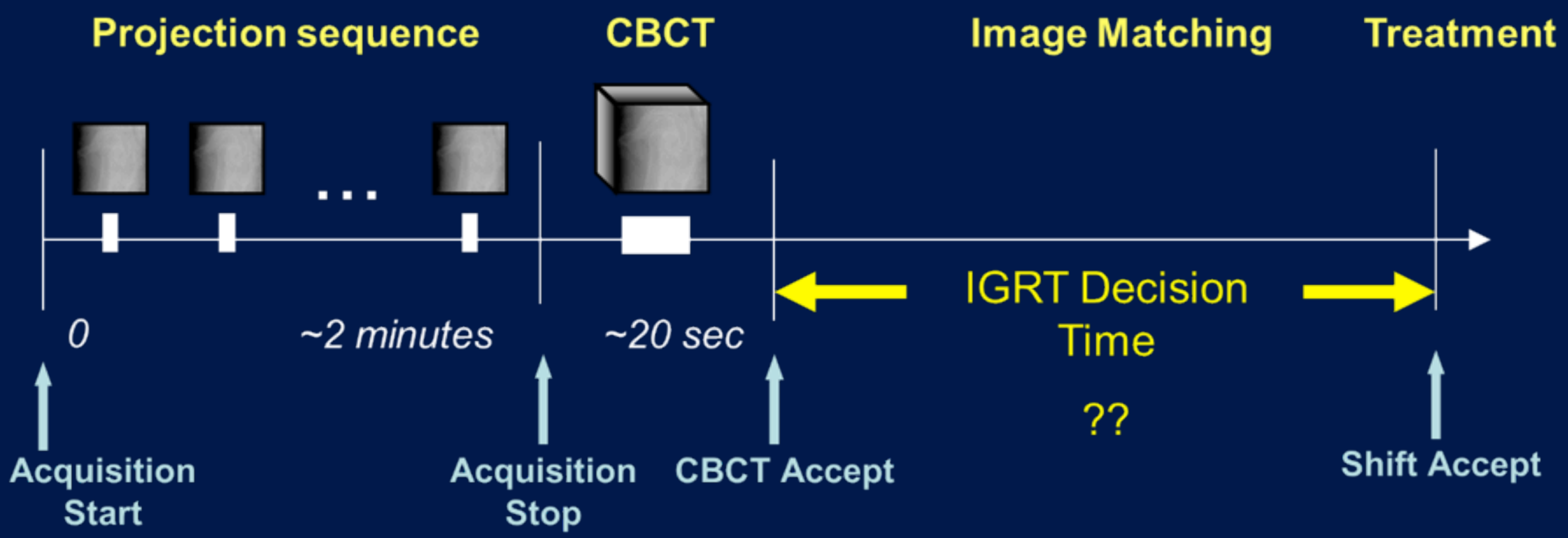
- Winnie Li, MRT(T), BSc (Hons), Princess Margaret Hospital

- CBCT-IGRT data from 2007 - 2010 across 8 linear accelerators were retrospectively analyzed

- IGRT-DTs from 4,592 patients, 117,301 localization CBCTs acquired over 4 years were analyzed
    - Patients comprised of 13 different treatment sites

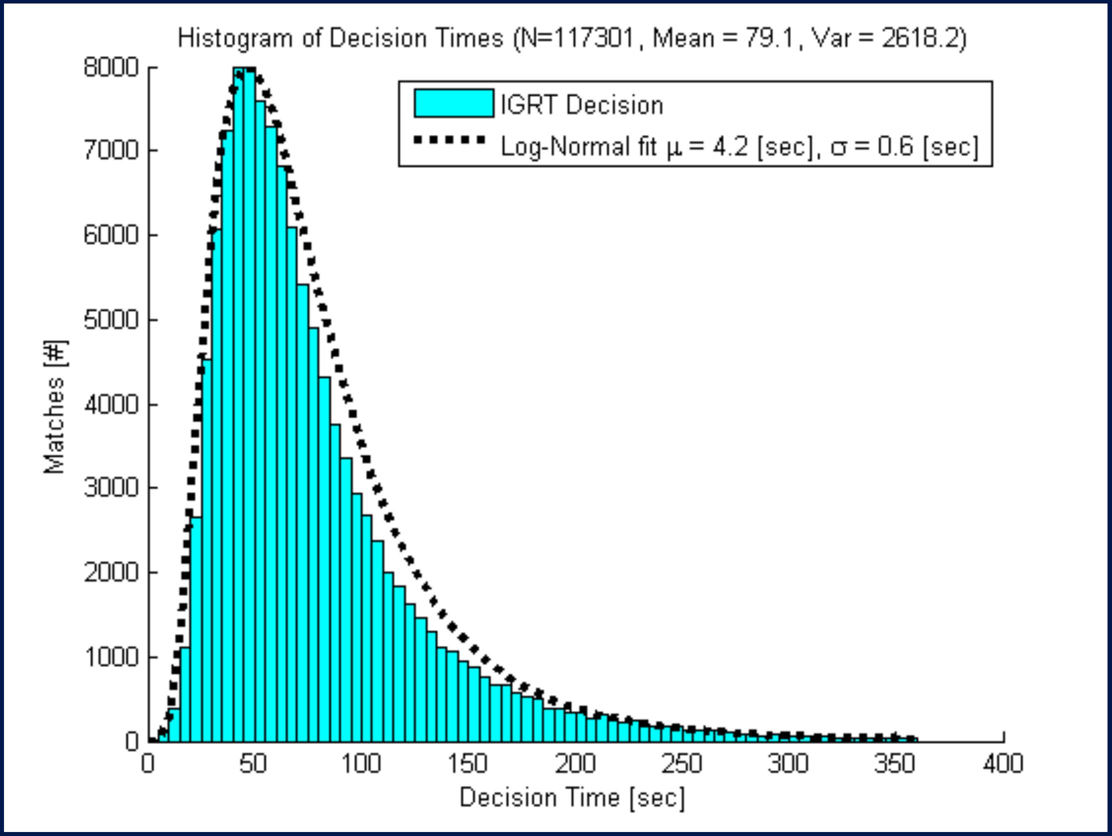
Introduction

- The “IGRT Decision Time” (IGRT-DT) = difference between the timestamp of image registration approval and timestamp of reconstruction acceptance by the end user (i.e. radiation therapists).



Results

- The mean 3D vector displacement was 4.8 ± 4.1 mm.
- The mean IGRT-DT was 79.1 ± 51.2 seconds.

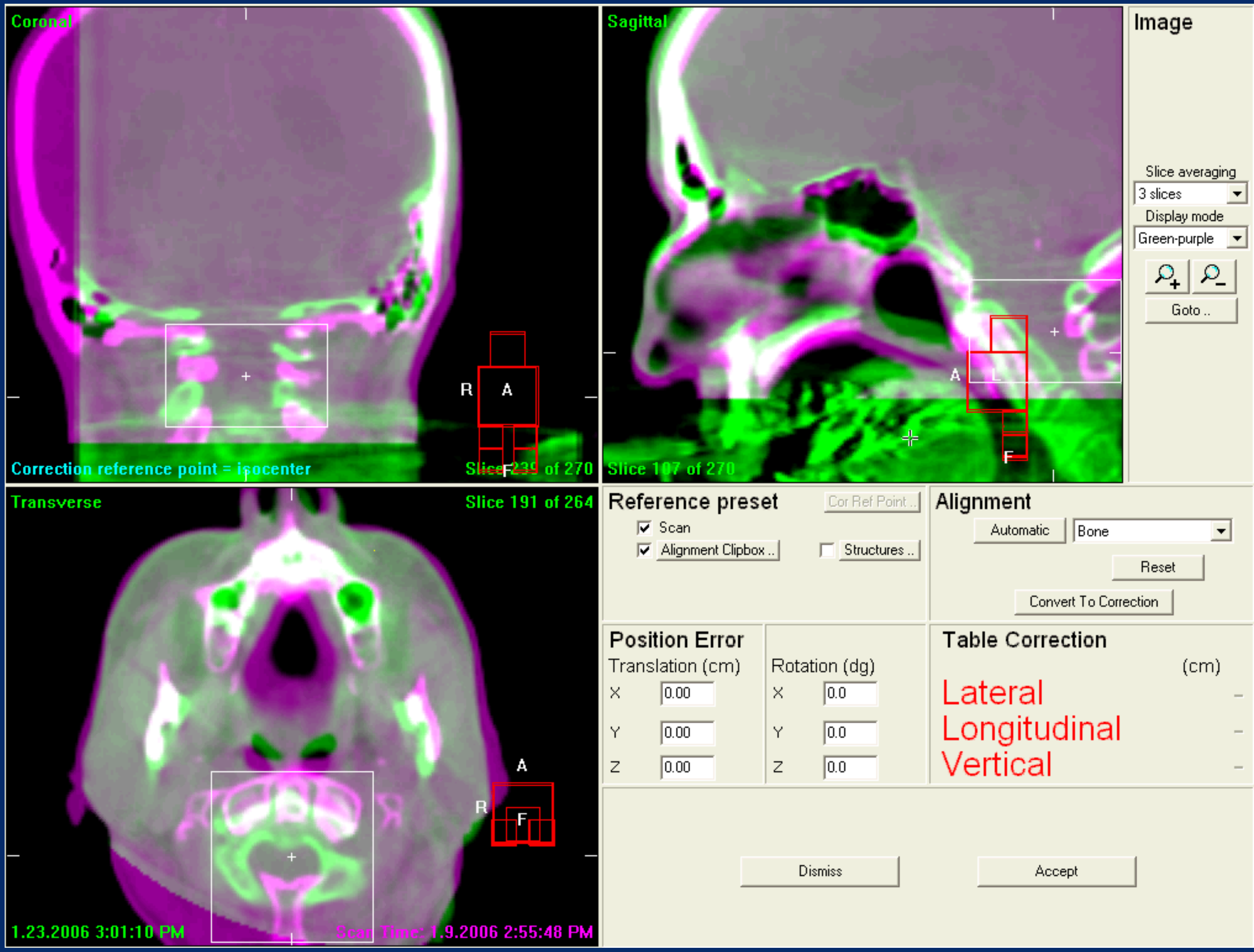


Moving from Image to Patient

- Standardize IGRT guidelines for anatomical sites
- Commission auto-registration for different sites
  - Yes! It often works!!!
  - Speeds up the process
- Create priorities for registration and build them into your PTV/PRV margins
  - If your priority is the tumor, you may need to increase your PRV
- Optimize image acquisition sequence to achieve the information you need in the image while minimizing dose to the patient

Limitation of Locally Rigid Registration

Intensity-based registration focused in the clip box



Neck:

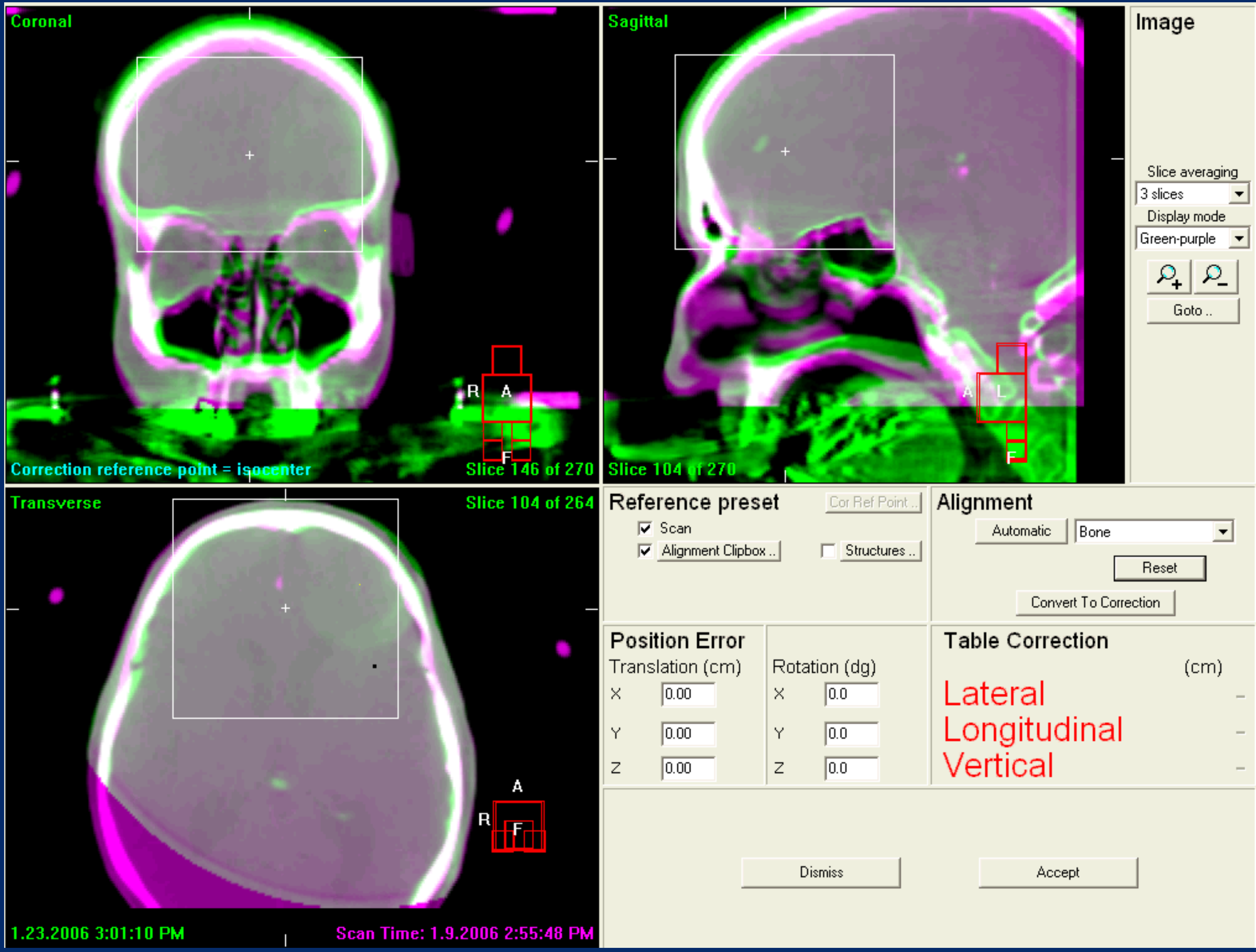
- 3.6, 5.3, 5.7 mm

Limitation of Locally Rigid Registration

Intensity-based registration focused in the clip box

Neck:
- 3.6, 5.3, 5.7 mm

Parietal/Sinus
- 1.7, 3.6, 1.1 mm



Limitation of Locally Rigid Registration

Intensity-based registration focused in the clip box

Neck:
- 3.6, 5.3, 5.7 mm

Parietal/Sinus
- 1.7, 3.6, 1.1 mm

Target:
- 1.1, 3.0, 0.7 mm

Summary

- Commissioning of your IGRT system is the first step
- Daily, Monthly, and Annual QA of IGRT is essential
- Moving from the Hardware to the Software to the Patient requires a multi-disciplinary team approach
  - Collaboration with the physicians on the site-specific IGRT protocols
  - Education of the dosimetrists on the uncertainties and incorporation into planning
  - Education of the therapists on how to implement the IGRT instructions