M D Anderson
Cancer Center
Orlando

TomoTherapy's Implementation of Image-guided Adaptive Radiation Therapy

Katja Langen, PhD

Research supported by TomoTherapy Inc.

Today's Lecture

- Introduction to helical tomotherapy
- Image guidance with TomoTherapy
- Adaptive radiation therapy with TomoTherapy

Introduction to helical Tomotherapy

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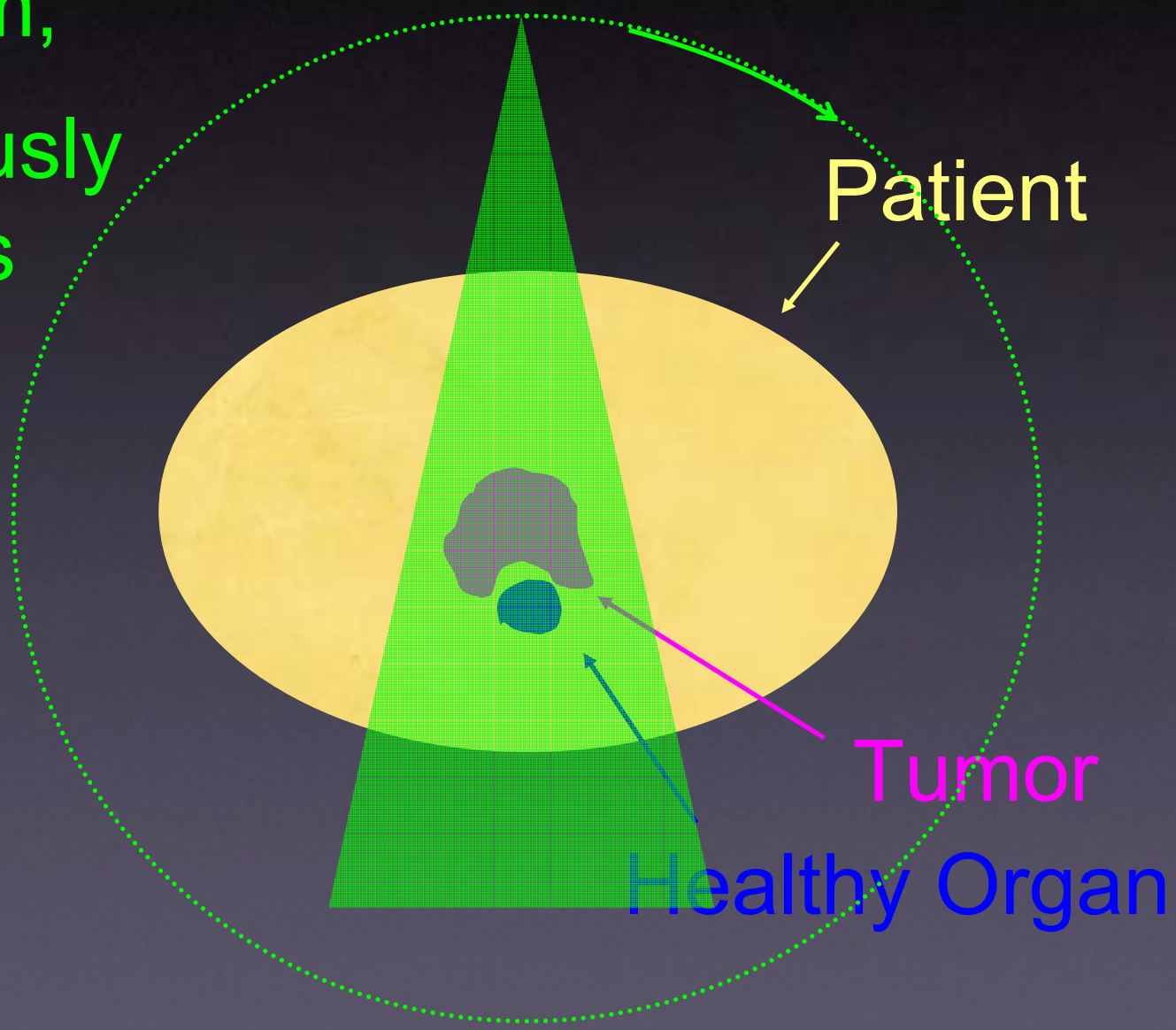
TomoTherapy

- Helical tomotherapy process to deliver IMRT
- Same hardware can be used to image (MVCT) patient (IGRT)

TomoTherapy

Fan beam,

continuously rotates



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TomoTherapy

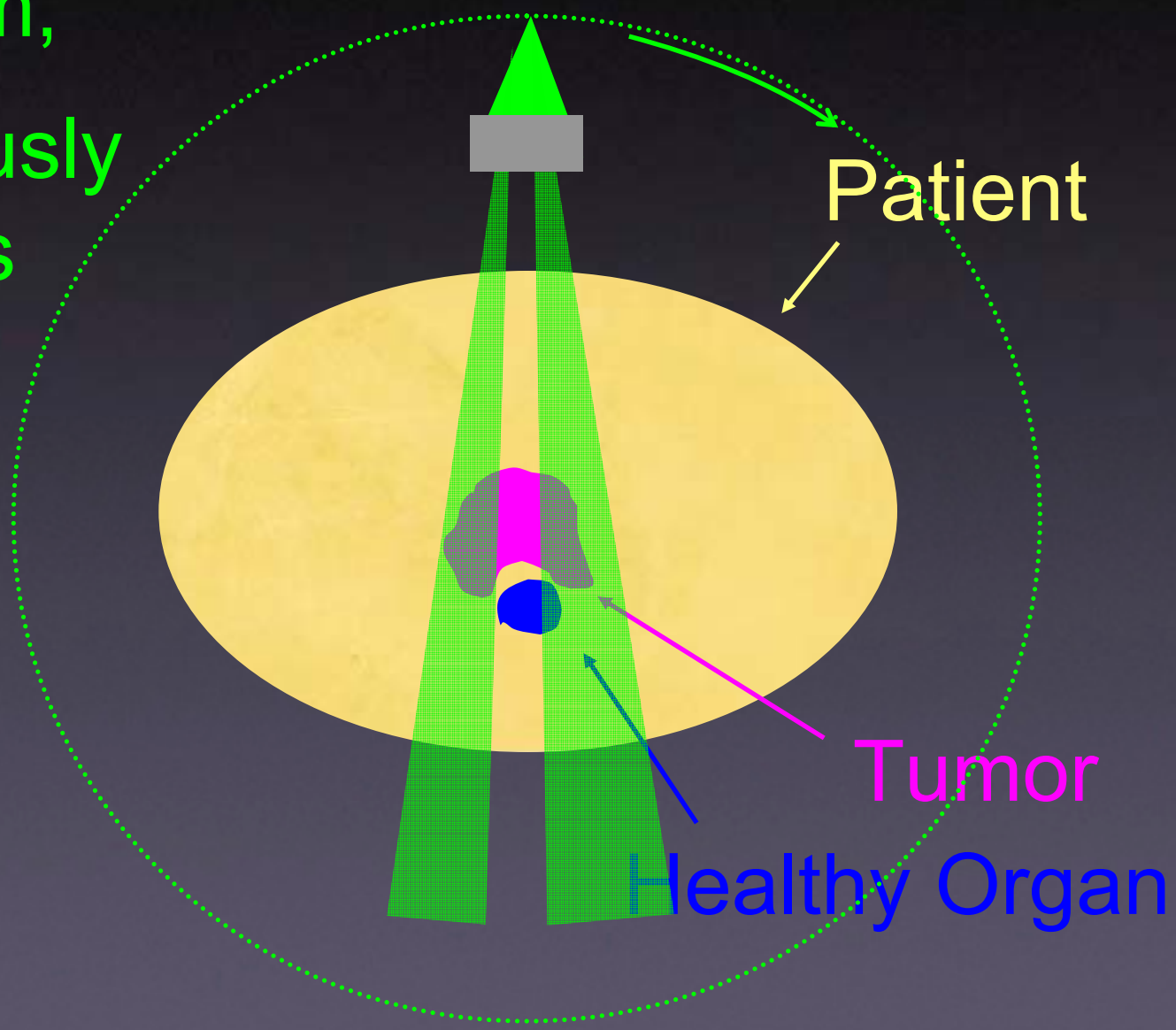
Divides beam into 64 beamlets

each beamlet can be on/off

TomoTherapy

Fan beam,

continuously rotates



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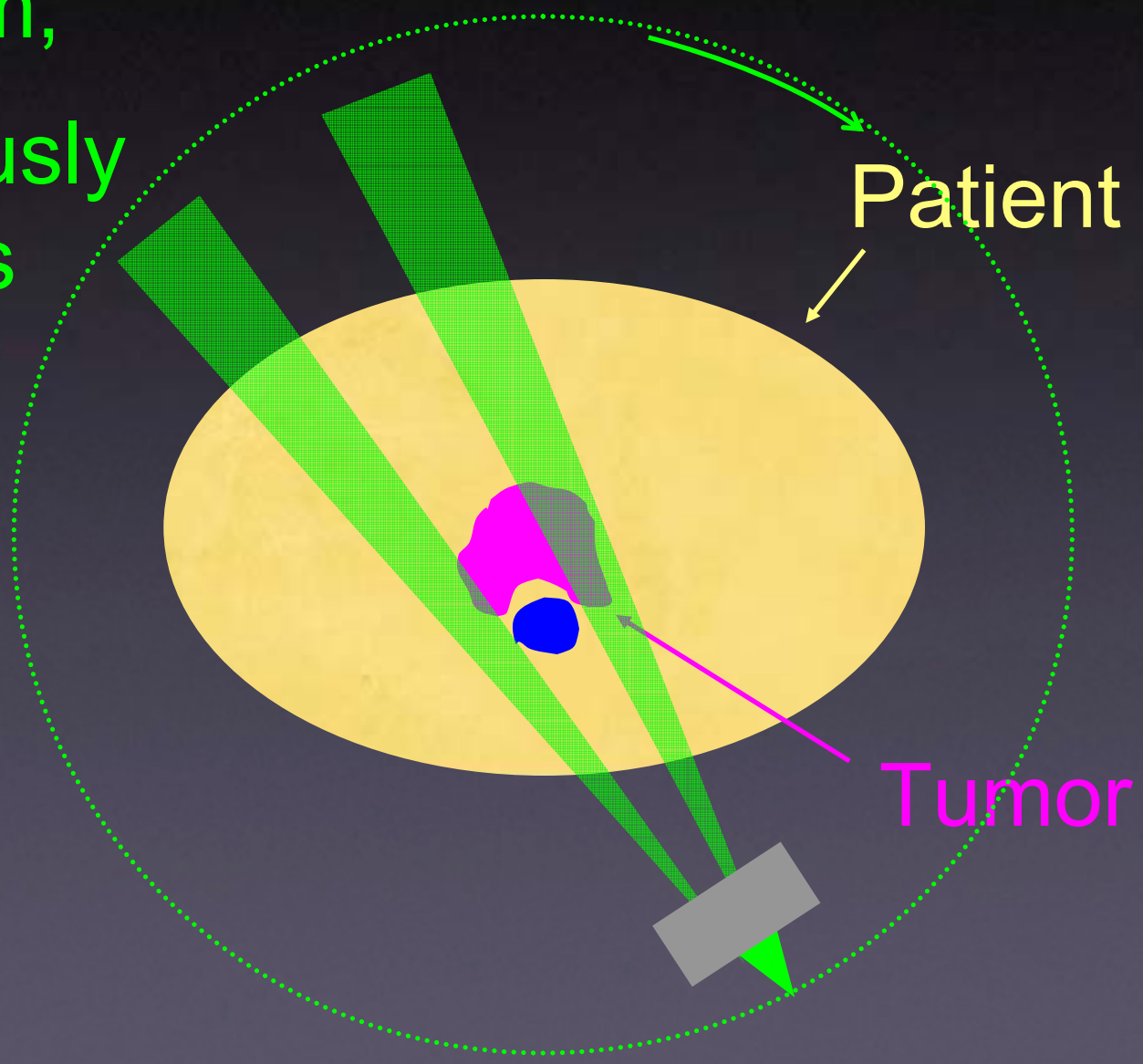
TomoTherapy

Fan beam,

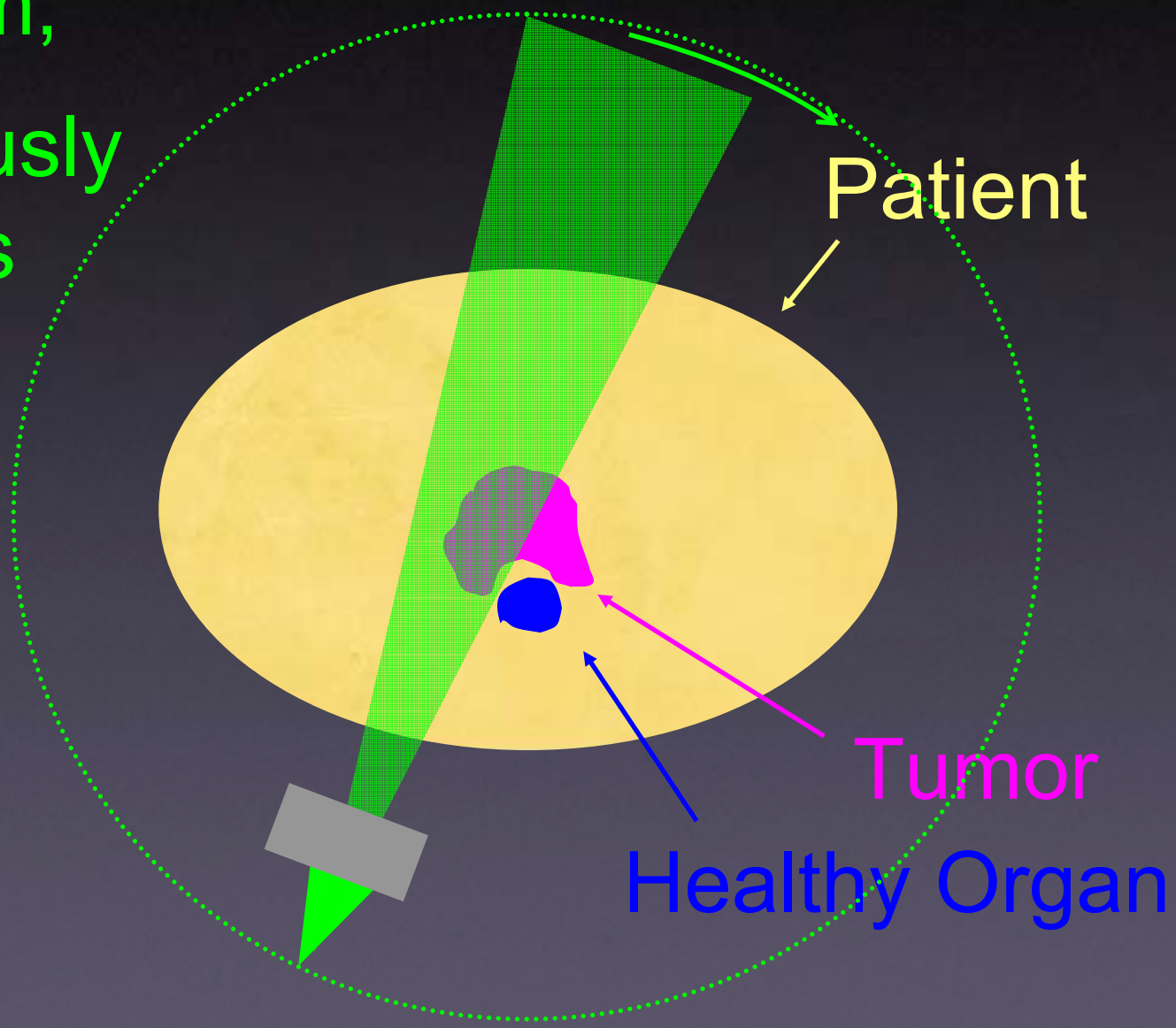
continuously rotates



TomoTherapy

Fan beam,

continuously rotates



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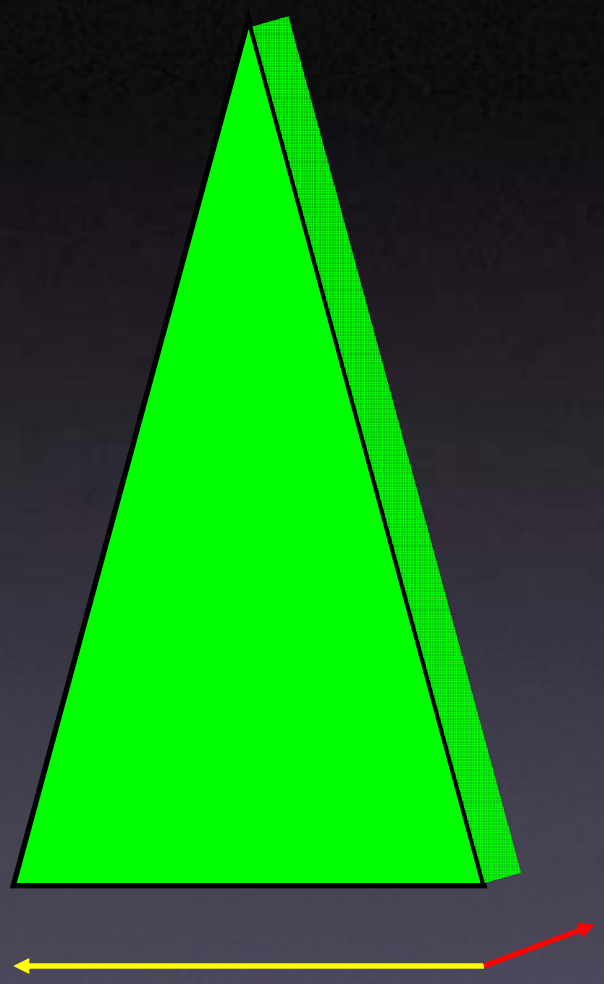
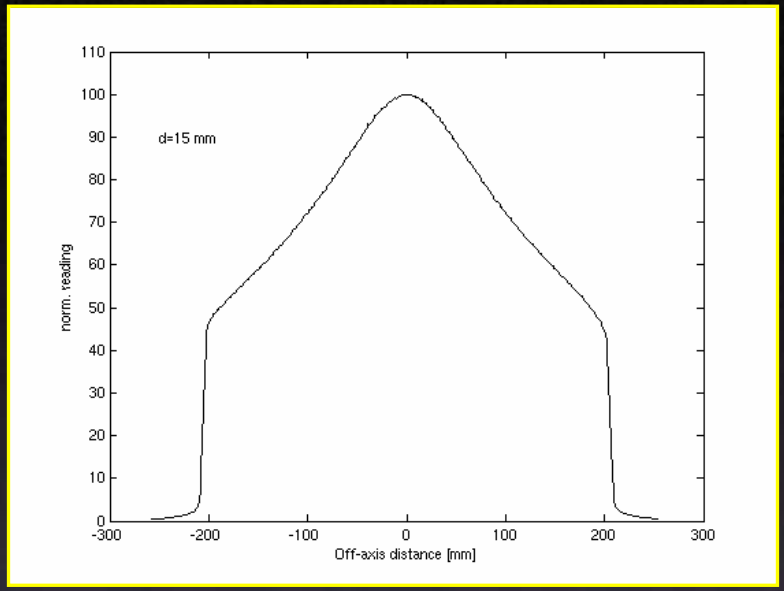
Fan Beam



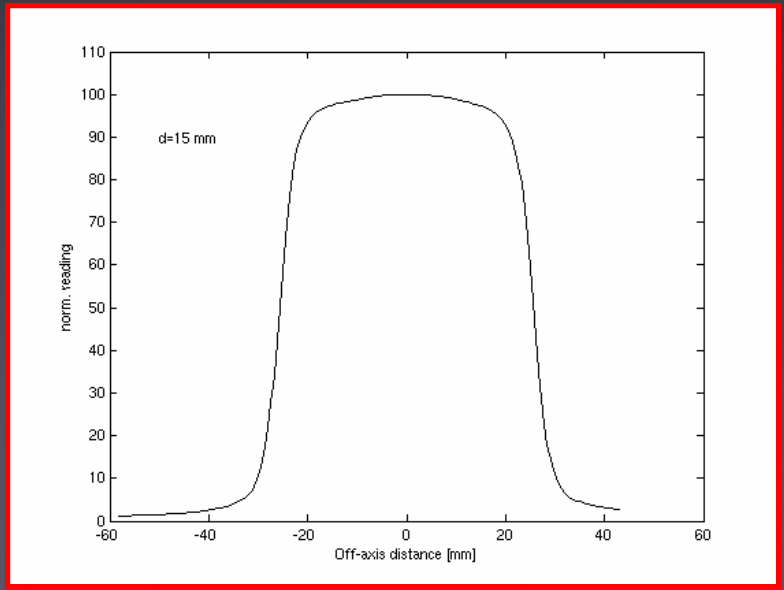
400 mm
lateral

10, 25, or 50 mm
longitudinal

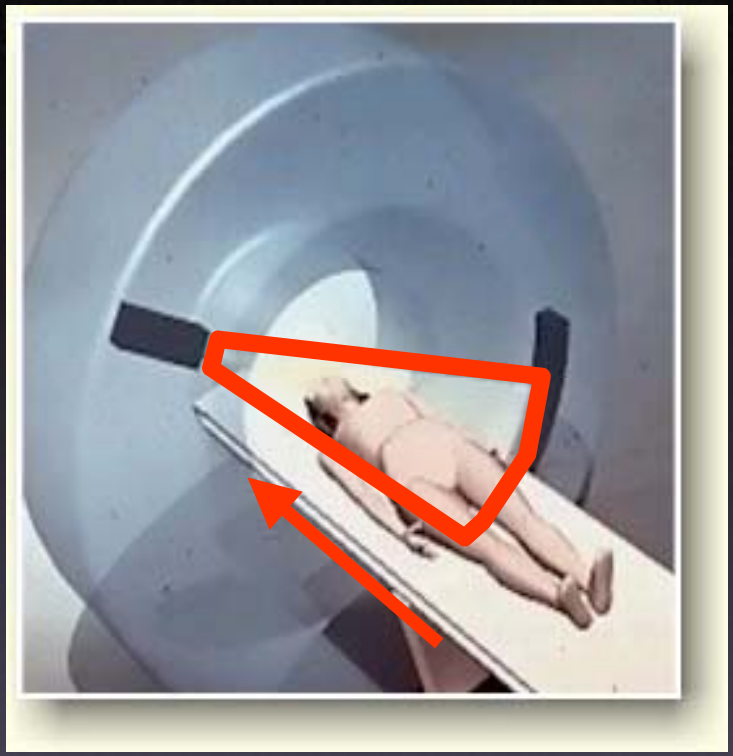
lateral

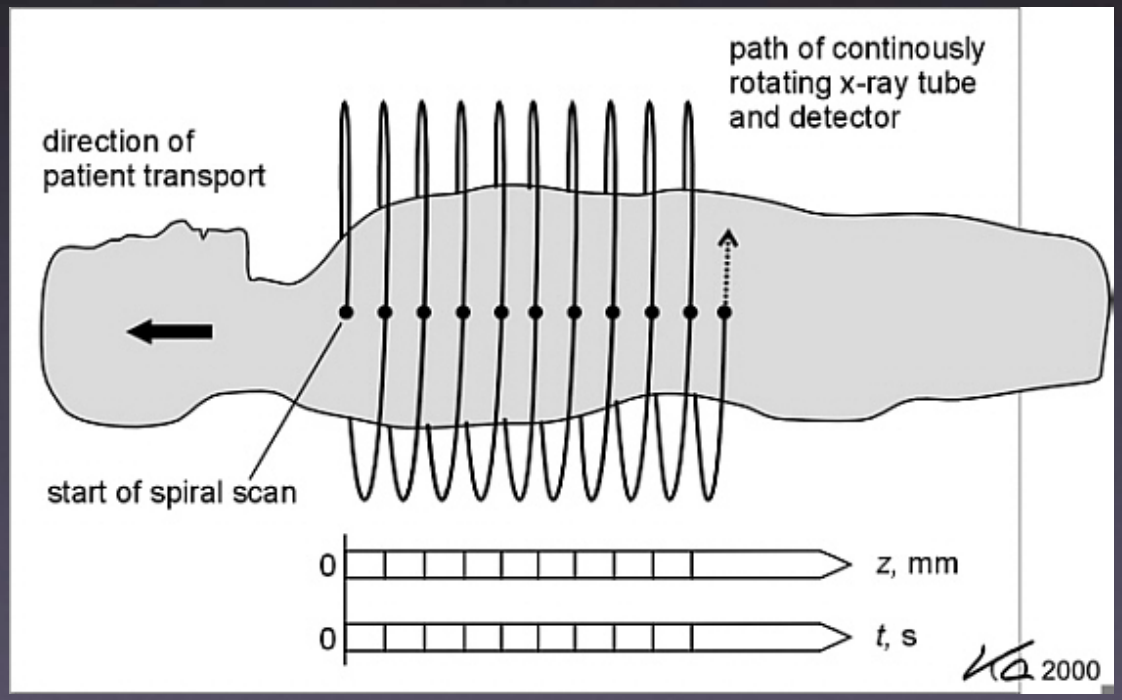


longitudinal



Helical Tomotherapy ?





from: W. Kalender, Computed Tomography: Fundamentals, System Technology, Image Quality, Applications

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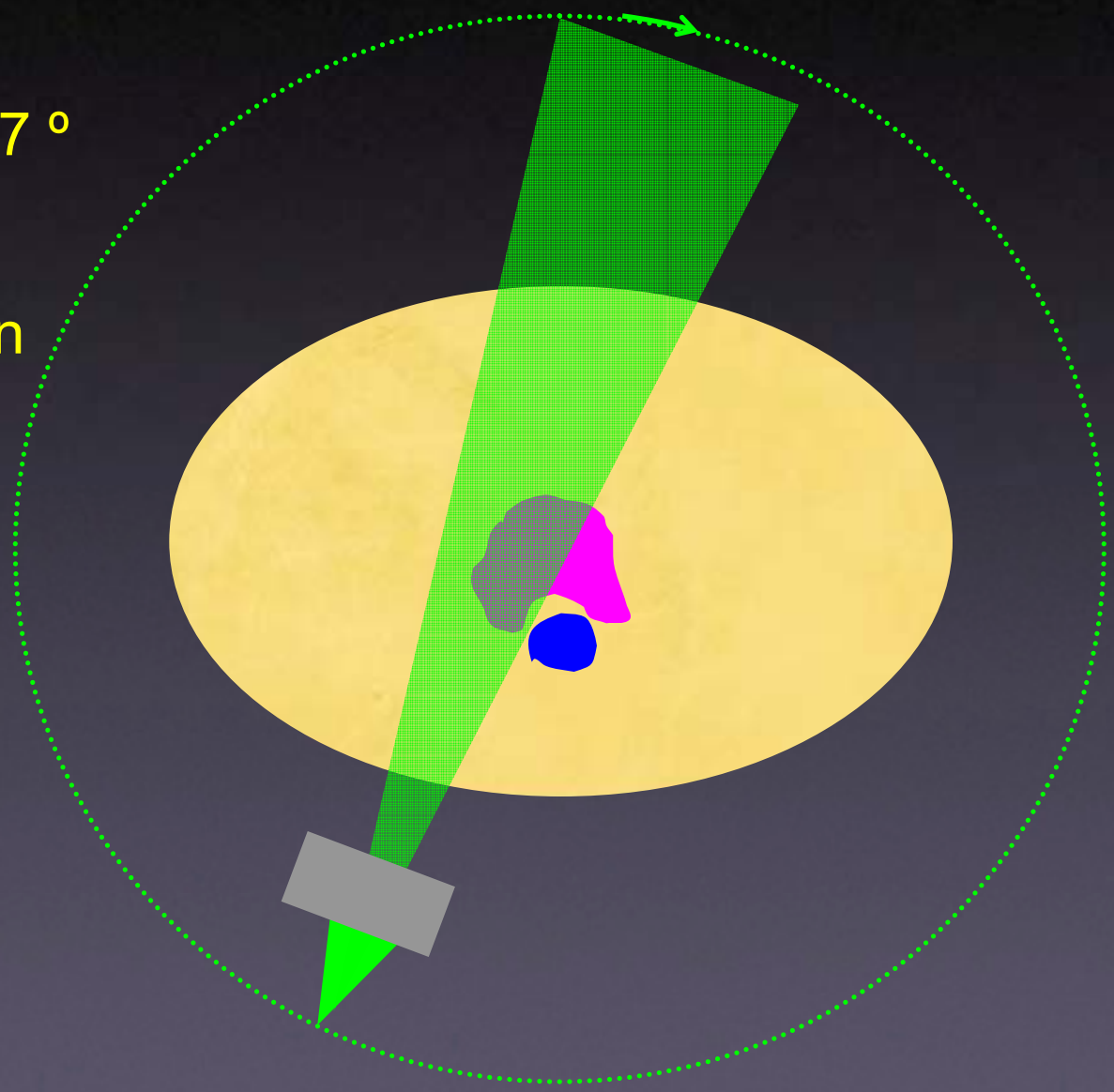
Delivery

- 51 projections per rotation: 360 º /51=7 º

-Temporal modulation leaf opening time during projection



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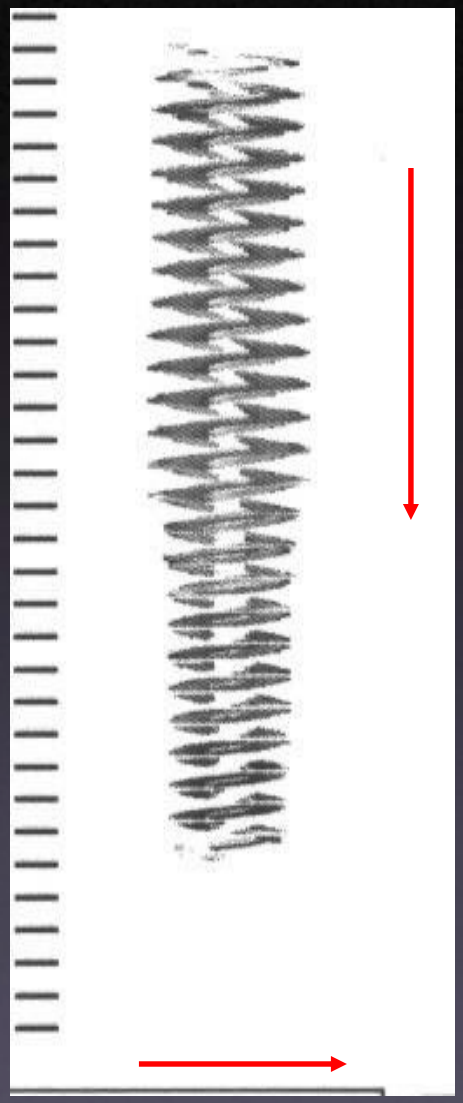
Delivery Instructions (Sinograms)

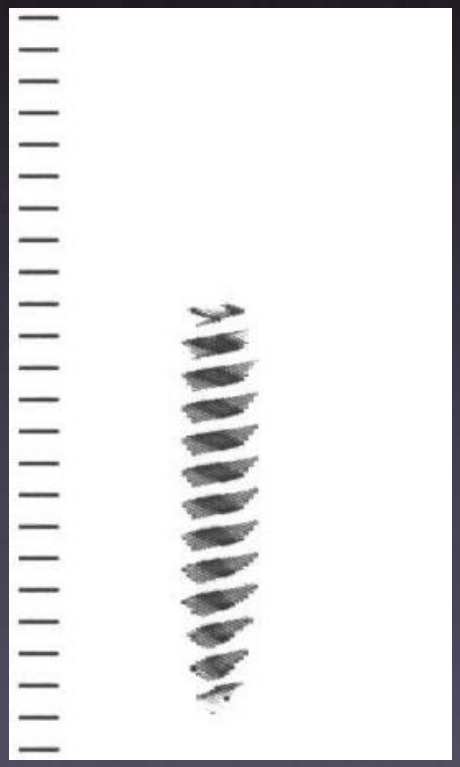
Head + Neck



Projections

64 Leafs

Prostate



-Typical gantry rotation:
15-20 seconds

-Typical treatment time:
Prostate: 5 Min
H+N: 7 Min

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The TomoTherapy unit at M D Anderson Orlando

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The TomoTherapy unit at M D Anderson Orlando

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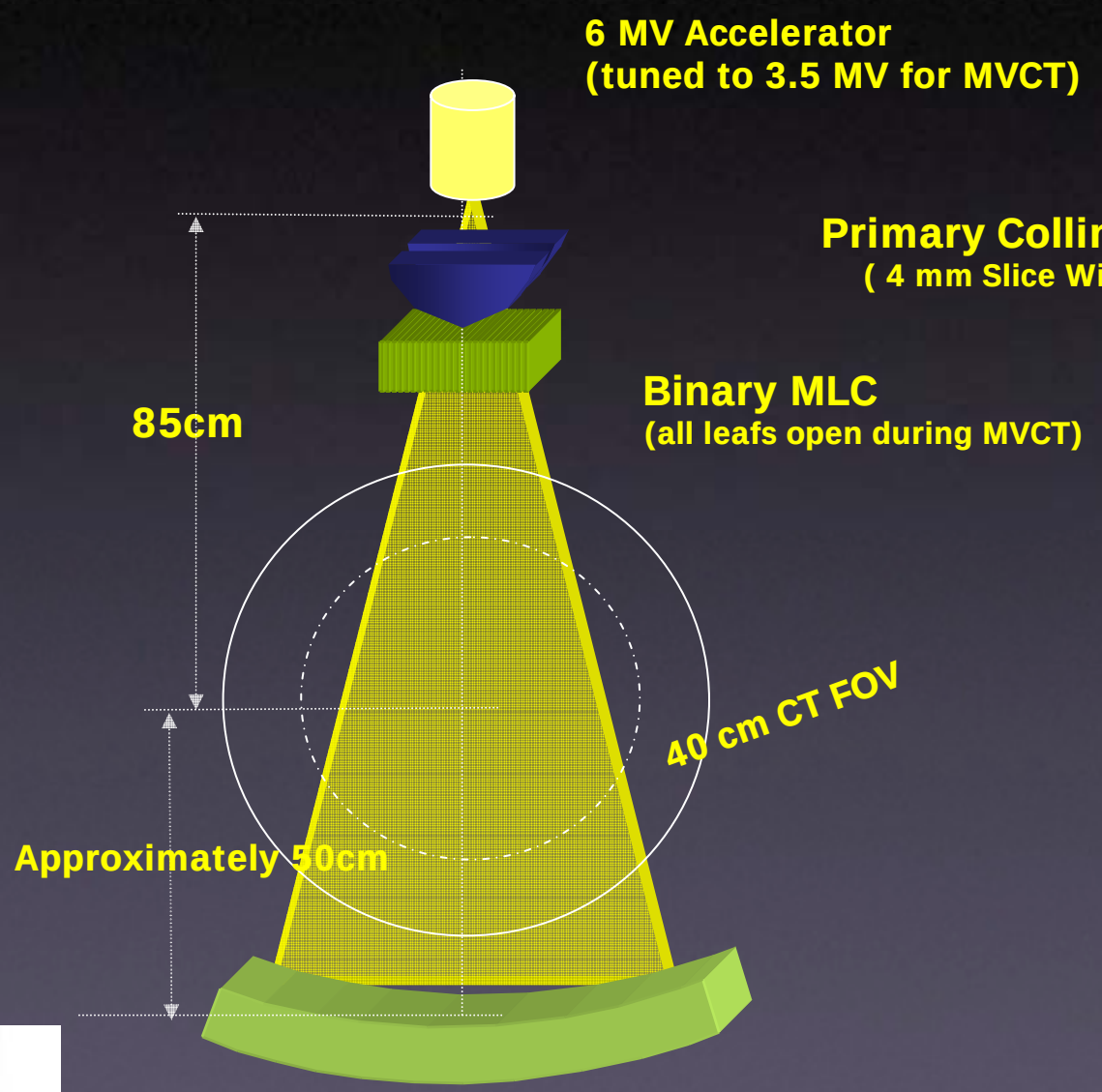
Megavoltage CT images



User can adjust:
-Scan range
-Pitch

Courtesy of:

TomoTherapy, Inc.

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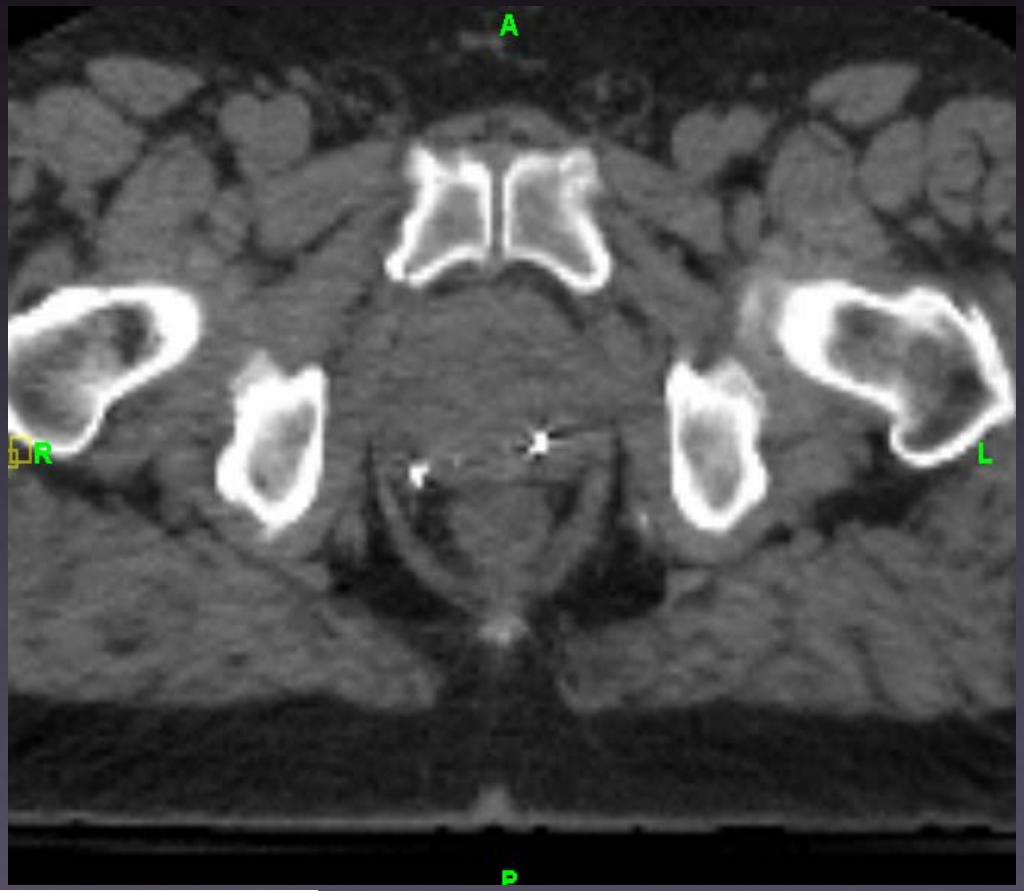
Patient Images: Prostate

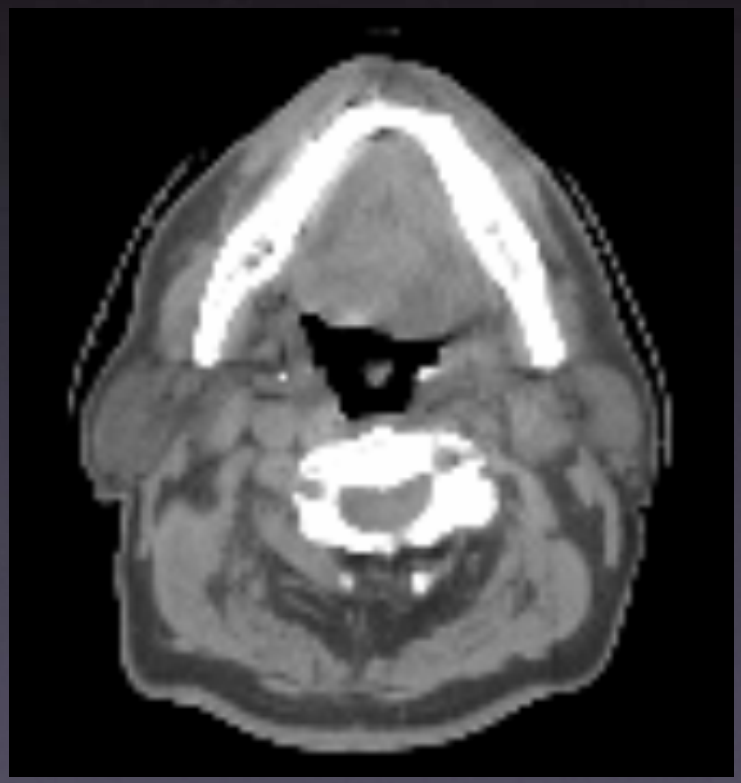
Diagnostic (kV) CT



Tomotherapy (MV) CT

Patient Images: Head and Neck

Diagnostic (kV) CT



Tomotherapy (MV) CT

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Image guidance with the TomoTherapy system

Terminology

Image-guided Radiation Therapy (**IGRT**):

Use images to position patient
-Portal images, Ultrasound, CT-based

Image-guided Radiation Therapy (**IGRT**) with TomoTherapy:

Megavoltage CT (MVCT) based

Image (MVCT) Quality ?

Helical Tomotherapy: MVCT Imaging Performance Characterization

- AAPM CT Phantom [Cardinal Health, Hicksville, NY].
  - Noise
  - Uniformity
  - Spatial Resolution
- Dosimetry
  - Multiple Scan Average Dose (MSAD) in 20 cm diameter acrylic phantom

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Meeks *et al.*, Med Phys, 32, pp 2673

Noise
Expressed as % of μ_{water}

Matrix	Pitch	Mean ROI "CT #"	ROI Standard Deviation	Noise
256	1.0	1024	25.4	
	1.6	1026		2.7
	2.4		25.3	2.7
512	1.0		35.4	3.7
		1027	35.5	3.7
	2.4	1029	36.2	3.8
768	1.0	1025	43.2	4.5
	1.6	1025	43.8	4.6
	2.4	1026	43.3	4.6
AcQSim 512	1.0	1005	18	1.9

Increases with recon matrix – independent of pitch values - worse than diagnostic CT scanners

Meeks *et al.*, Med Phys, 32, pp 2673

Uniformity
Maximum Peripheral to Central Deviation

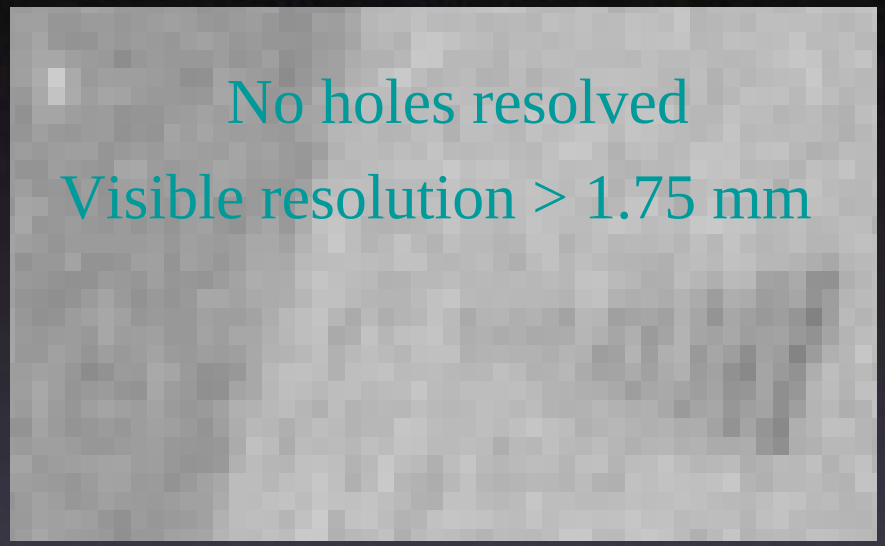
Matrix	Pitch	Maximum Peripheral Variation (%)	Uniformity Index	Mean Center "CT"	Mean Peripheral "CT"
256	1.0	0.99	**99.5**	1015	
	1.6	0.97	**99.6**		
	2.4	1.03			1022
512	1.0	[illegible]		1020	1029
	[illegible]	[illegible]	**99.6**	1019	1028
	[illegible]	[illegible]	**99.5**	1021	1031
	1.0	0.94	**99.5**	1019	1027
	1.6	0.80	**99.6**	1019	1026
	2.4	0.89	**99.6**	1019	1027
AcQSim 512	1.0	0.55	**99.6**	1006	1005

Independent of pitch/recon matrix – values comparable to diagnostic CT scanners

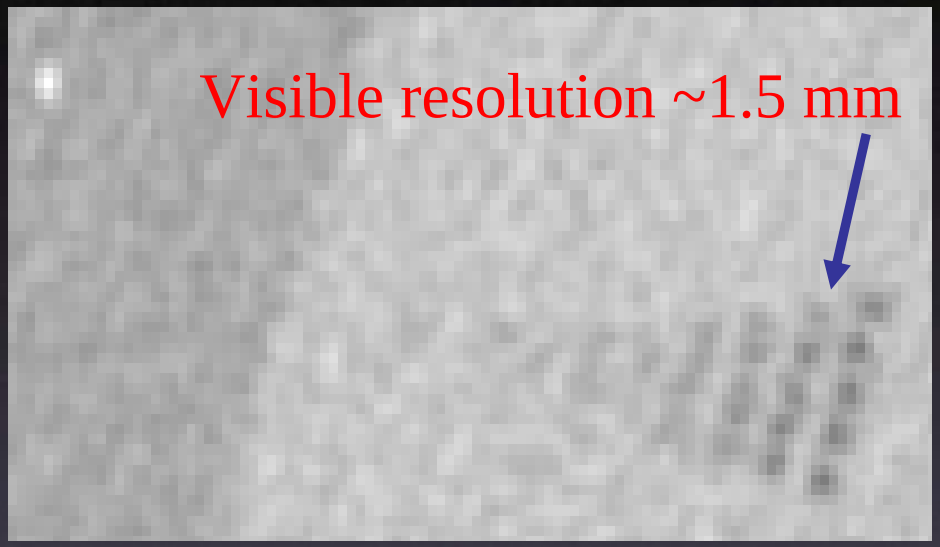
Meeks *et al.*, Med Phys, 32, pp 2673

Spatial Resolution: Qualitative Determination

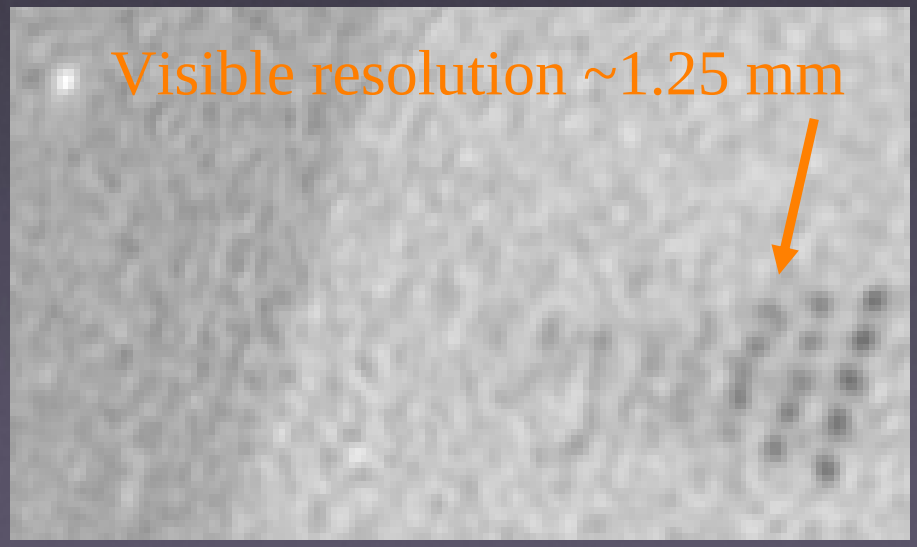
256x256 matrix



512x512 matrix



768x768 matrix



Meeks *et al.*,
Med Phys, 32, pp 2673

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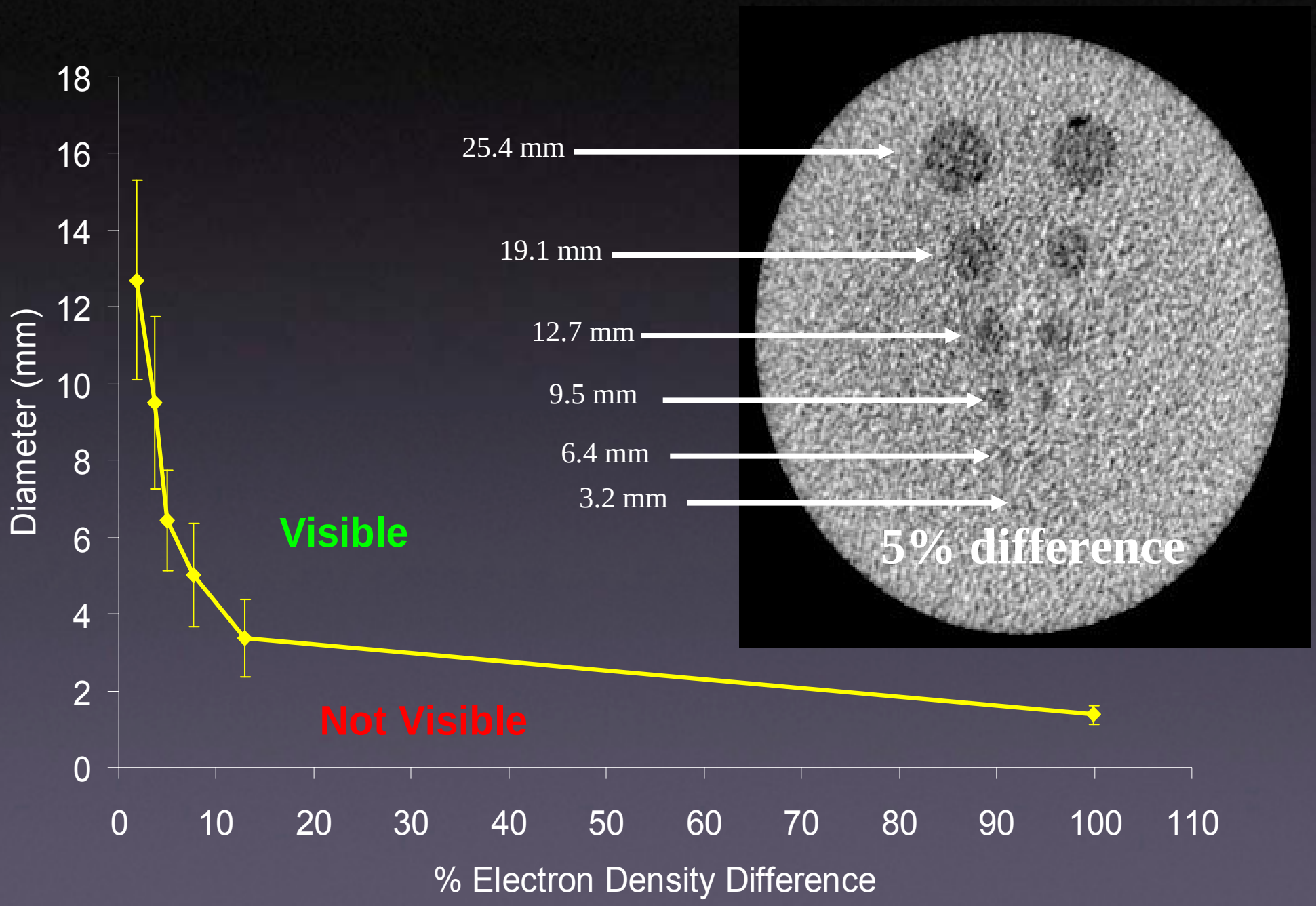
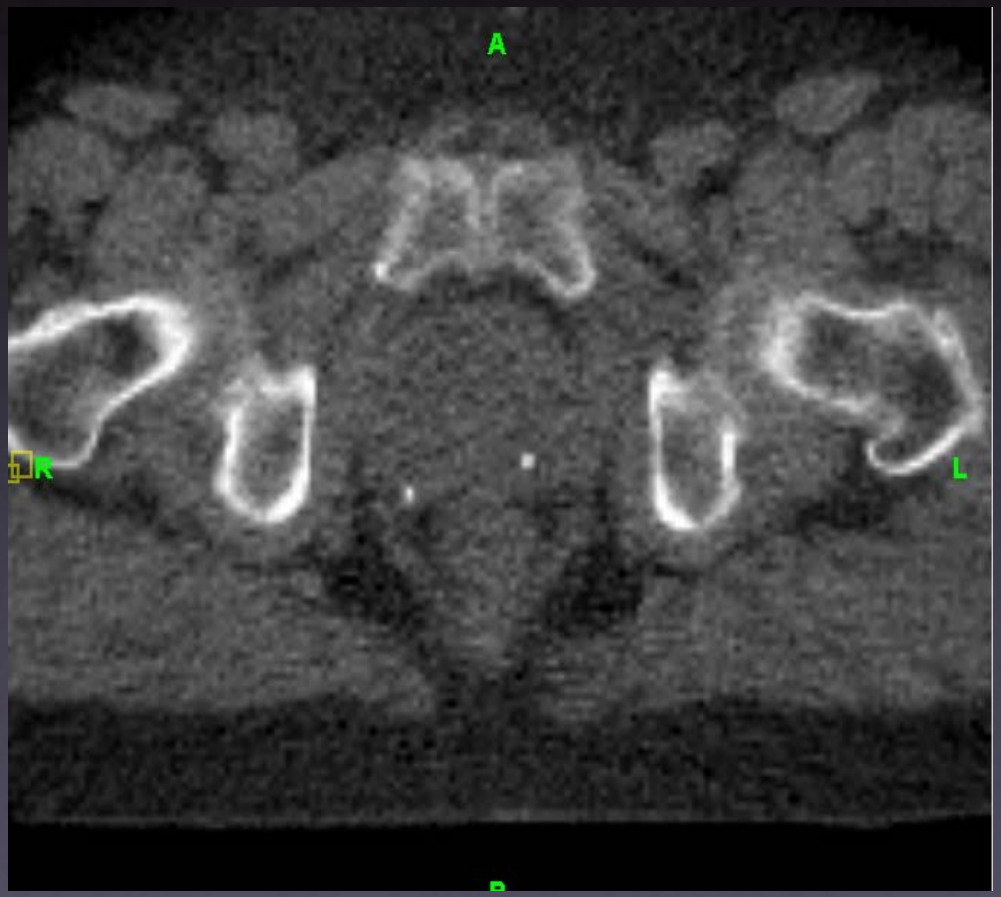
Contrast Detail

Meeks *et al.*, Med Phys, 32, pp 2673



Patient Images



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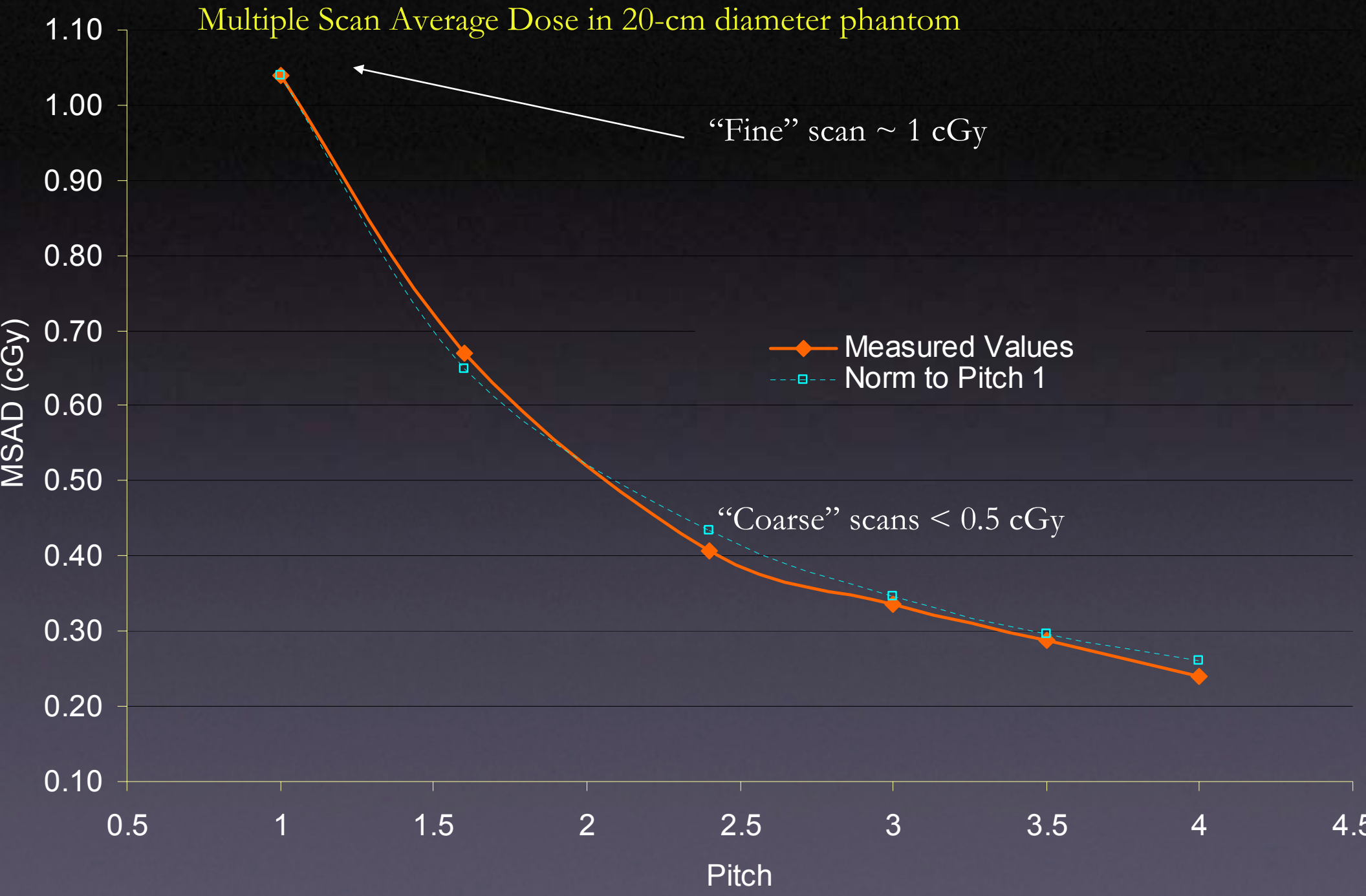
MVCT Dose

Multiple Scan Average Dose in 20-cm diameter phantom



Meeks *et al.*, Med Phys, 32, pp 2673

Summary

- Uniformity is comparable to diagnostic CT scanners while noise is worse
- Spatial resolution using 512x512 matrix is ~1.5 mm
- Dose: ~1 cGy for “fine” setting (pitch of 1) ; dose decreases with “looser” pitch
- **Image Quality is acceptable for patient alignment, and is also acceptable for delineation of many soft tissue structures.**

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Meeks *et al.*, Med Phys, 32, pp 2673

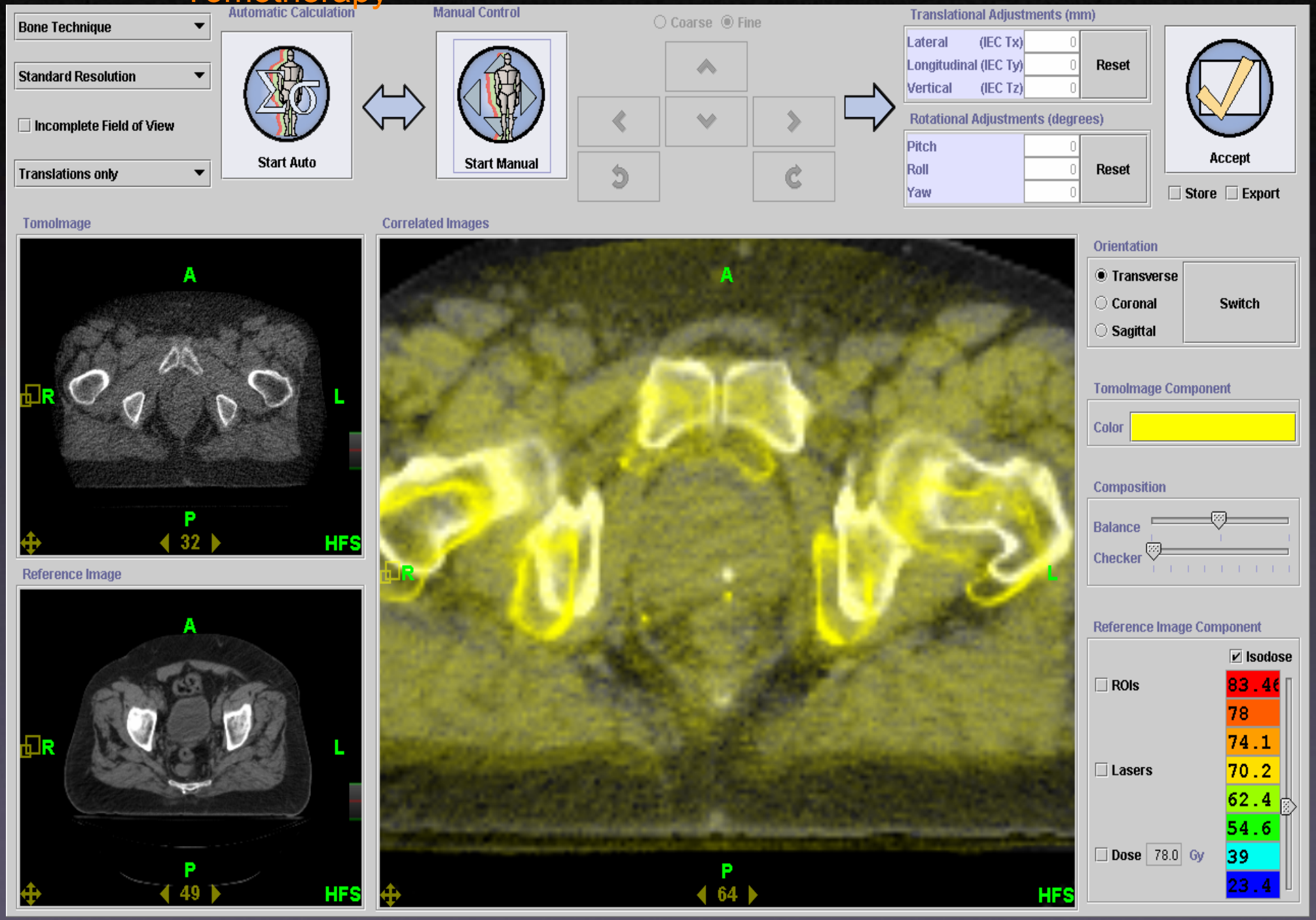
Average In-Room Times

- 5 minutes for setup
- 3-5 minutes MVCT scan
- 5 minutes reconstruction and registering MVCT to KVCT and shift patient
- 5-10 minutes beam on time
- 5 minutes assist patient out

IGRT

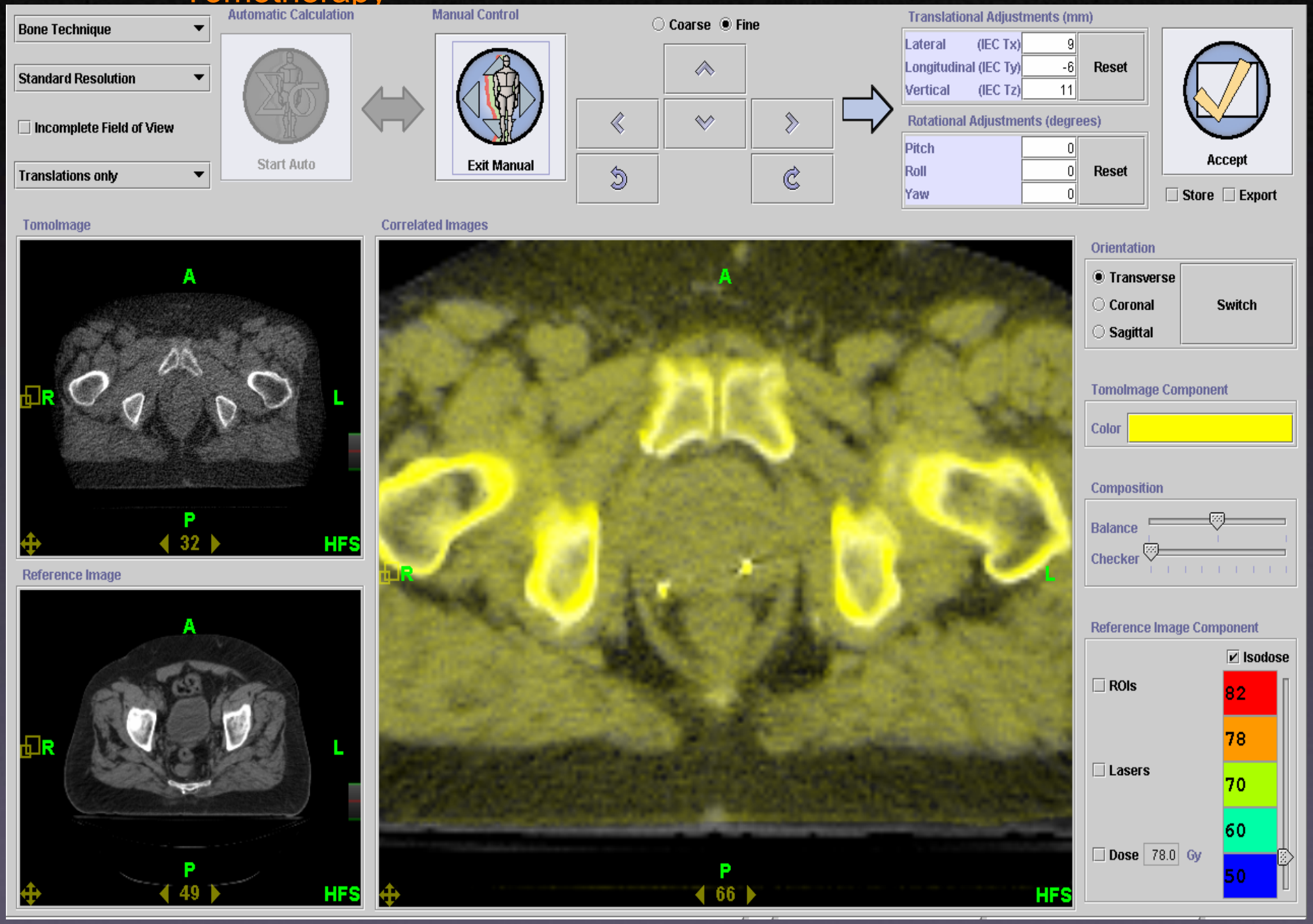
Prostate IGRT: Helical Tomotherapy

Transverse, not aligned



Prostate IGRT: Helical Tomotherapy

Transverse, aligned



Prostate IGRT: Helical Tomotherapy

Sagittal, aligned

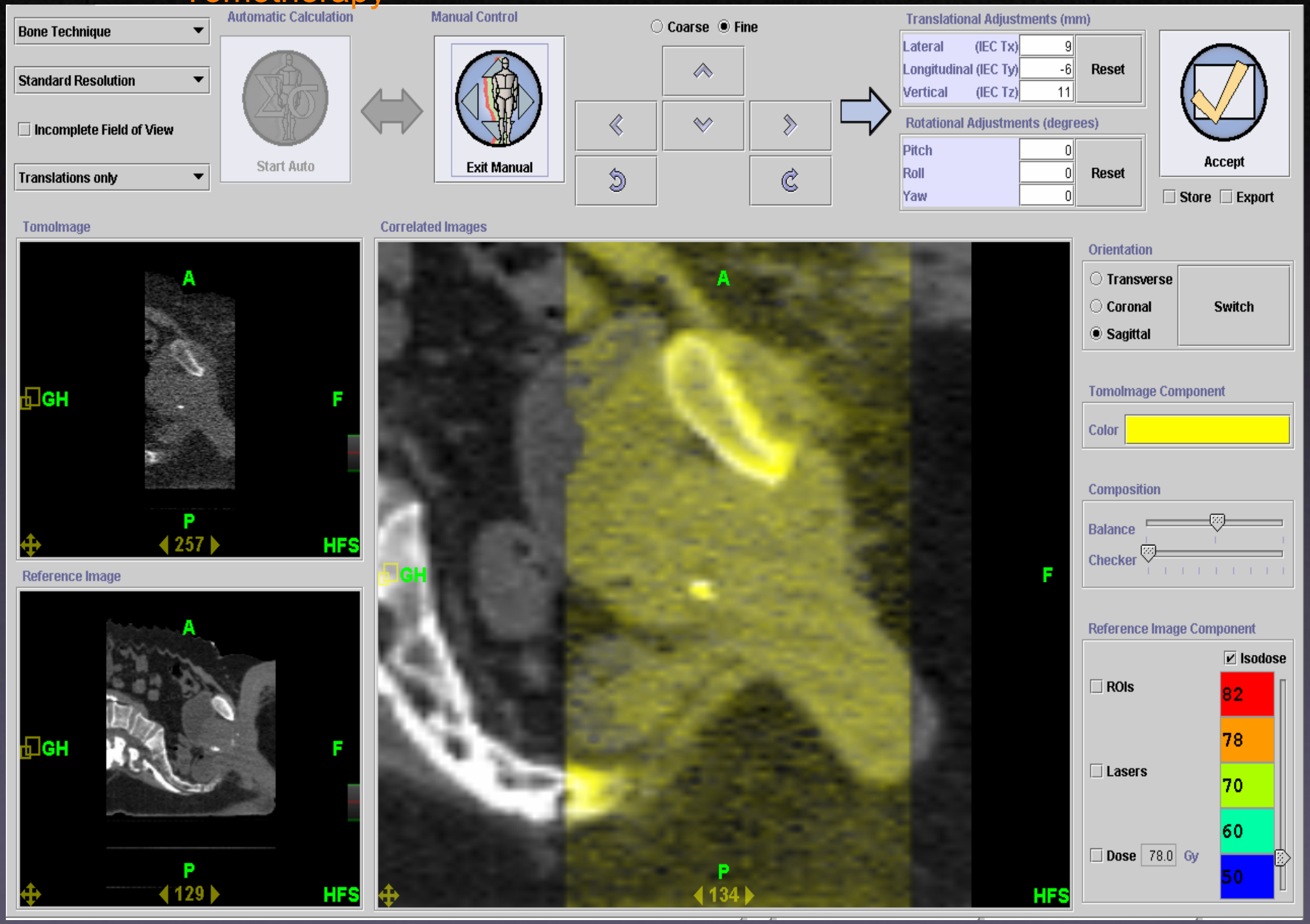
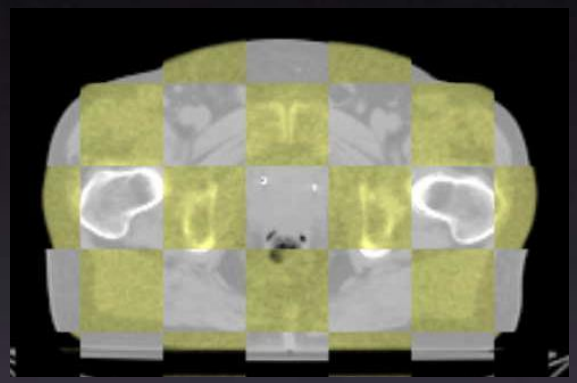
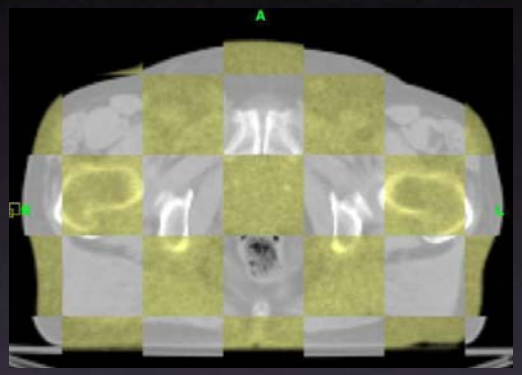


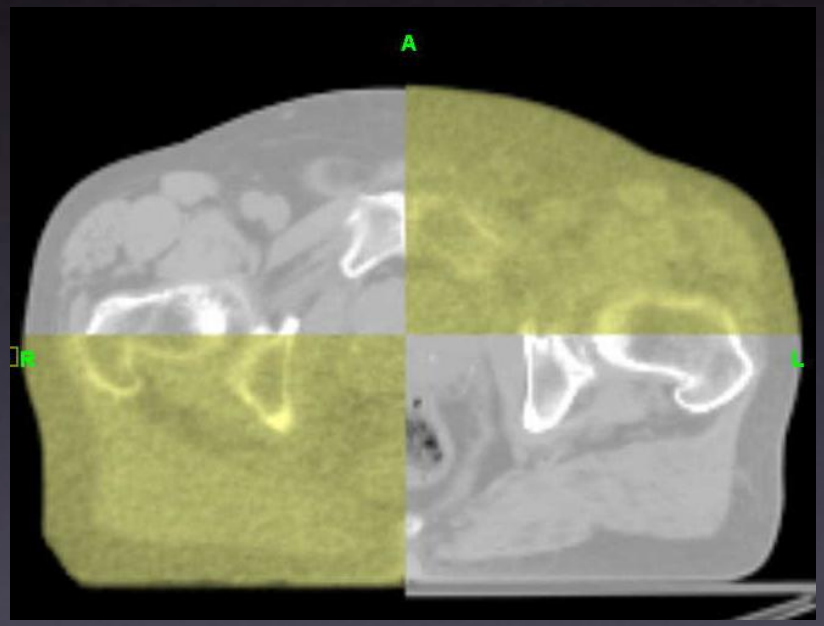
Image Registration for Prostate cases ?

Fiducial marker based

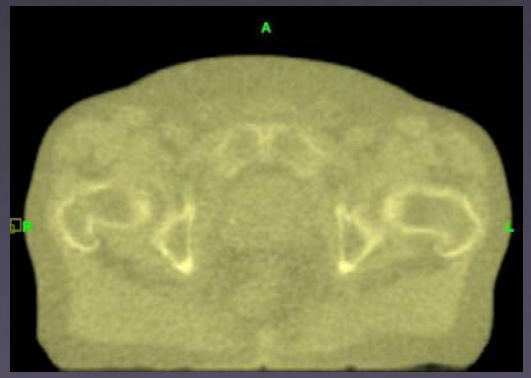


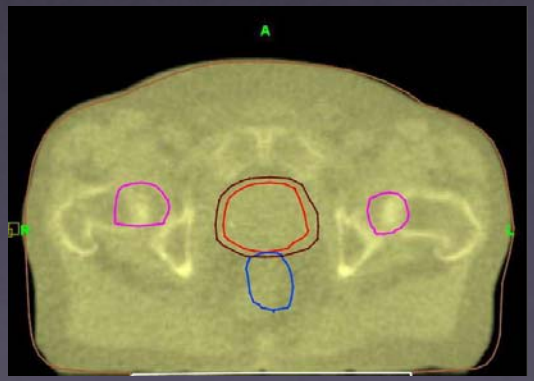


Anatomy based



Contour based





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Prostate alignment study

RT: Marker, Anatomy, Contour
MD: Marker, Anatomy, Contour

112 image pairs
3 patients

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Langen et al., IJROBP, 62, pp 1517

RT vs MD registration

Difference ≥ 5 mm

Marker	Anatomy	Contour
A/P: 1 % S/I: 2 % Lat.: 1 %	A/P: 5 % S/I: 10 % Lat.: 0 %	A/P: 17 % S/I: 31 % Lat.: 3 %

Langen et al., IJROBP, 62, pp 1517

RT vs MD registration

Difference ≥ 3 mm

Marker	Anatomy	Contour
A/P: 2 % S/I: 12 % Lat.: 2 %	A/P: 15 % S/I: 32 % Lat.: 3 %	A/P: 48 % S/I: 52 % Lat.: 24 %

Langen et al., IJROBP, 62, pp 1517

Conclusions of alignment study

Implanted marker based alignment have least inter-user variability

Anatomy-based alignments outperform contour-based alignments

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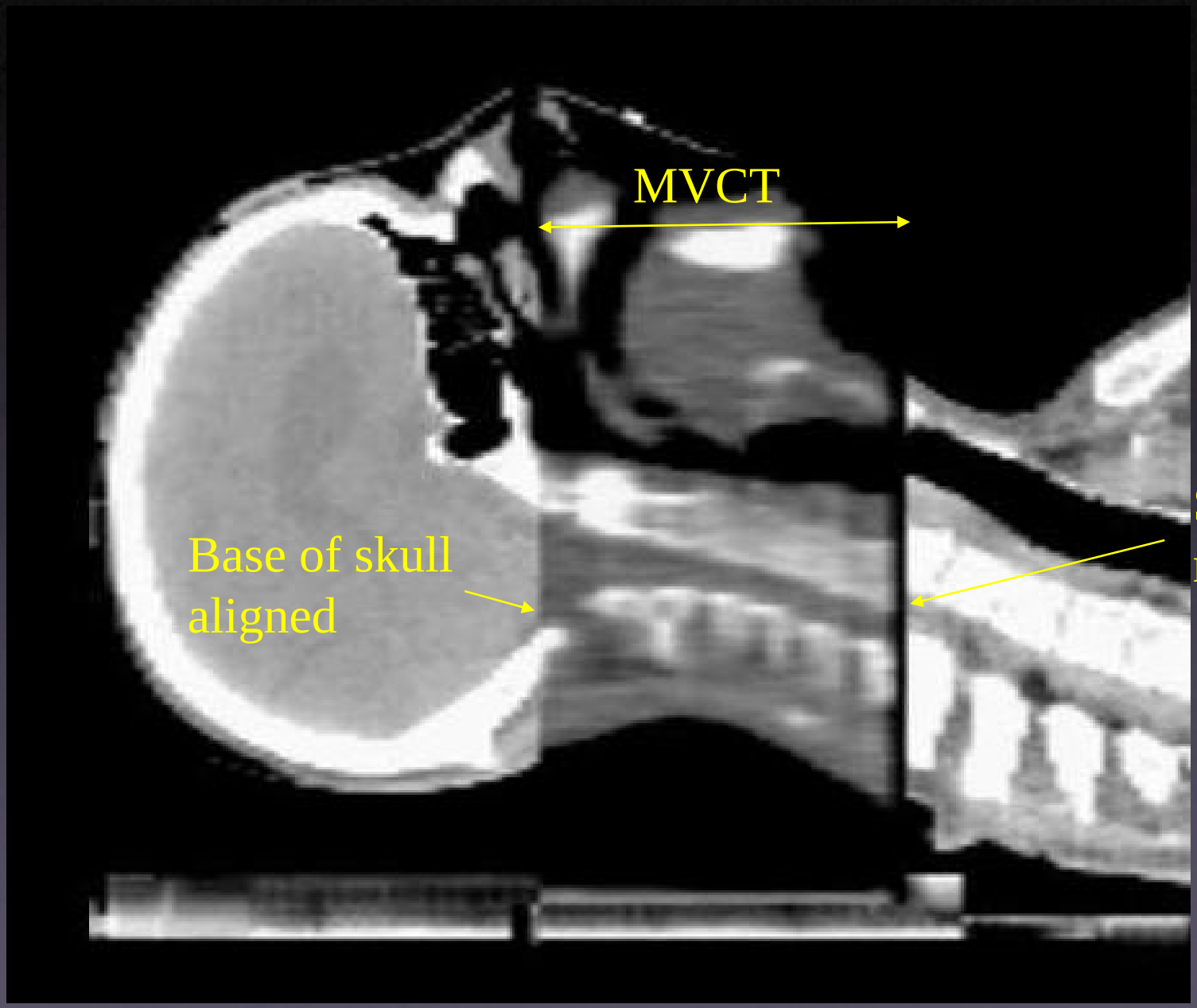
Langen et al., IJROBP, 62, pp 1517

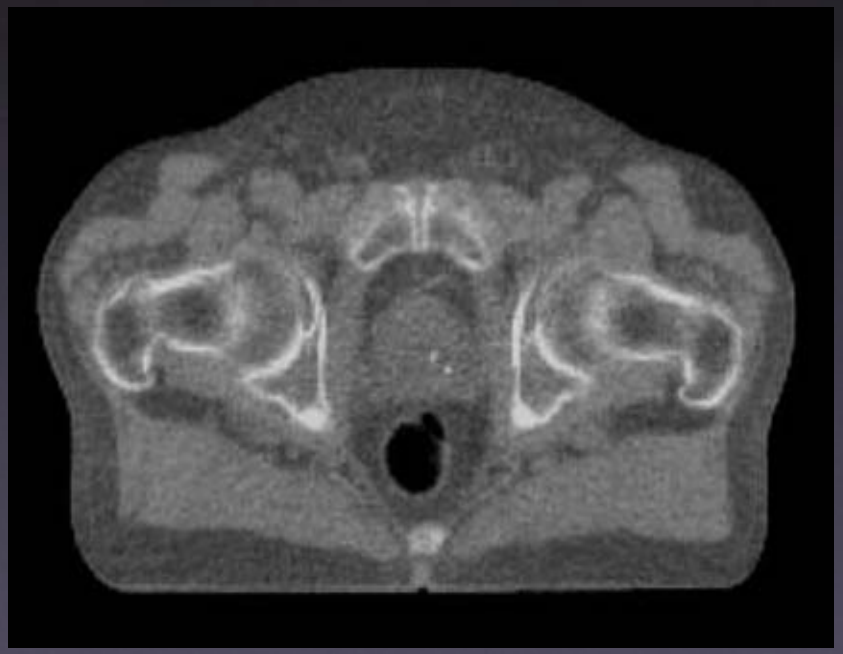
Head and Neck alignment: bony anatomy



IGRT and ART, do we need both ?

Daily-IGRT, why ART ?

Deformation in the Pelvis
Same patient, different days



Dosimetric consequence ?

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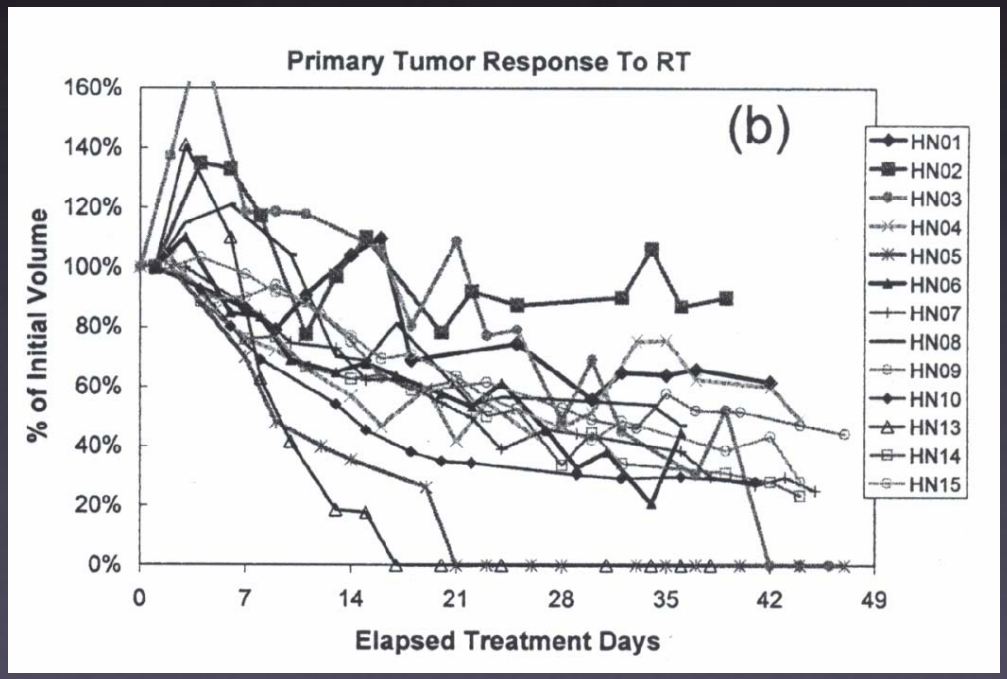
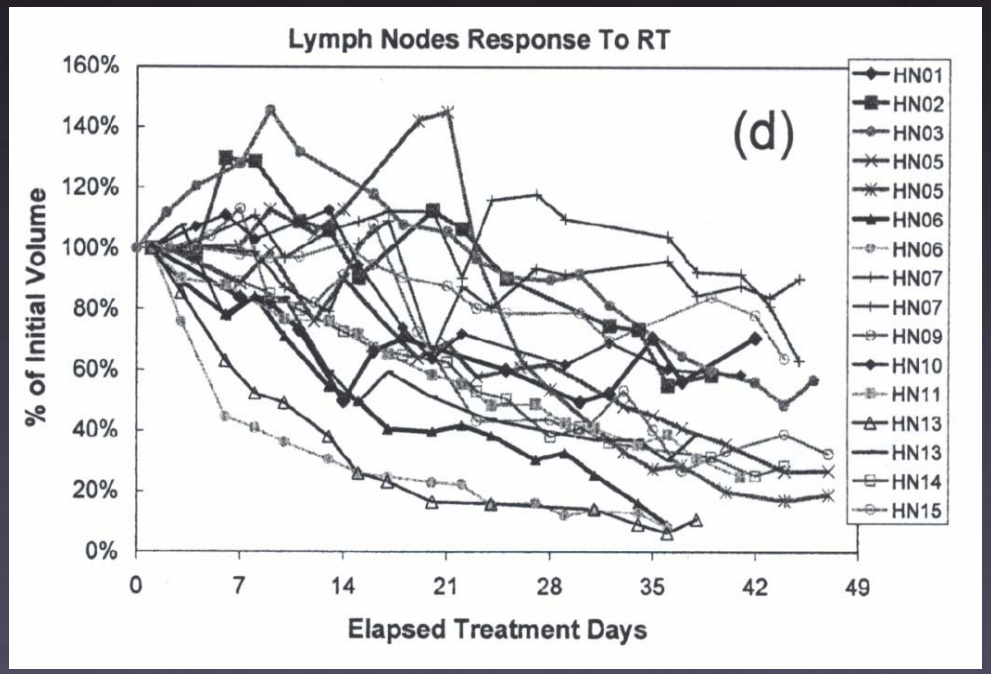
Progressive deformation

Barker (2004): 14 H+N patients, 13-20 repeat CT, in-room CT

Observation of tumor regression





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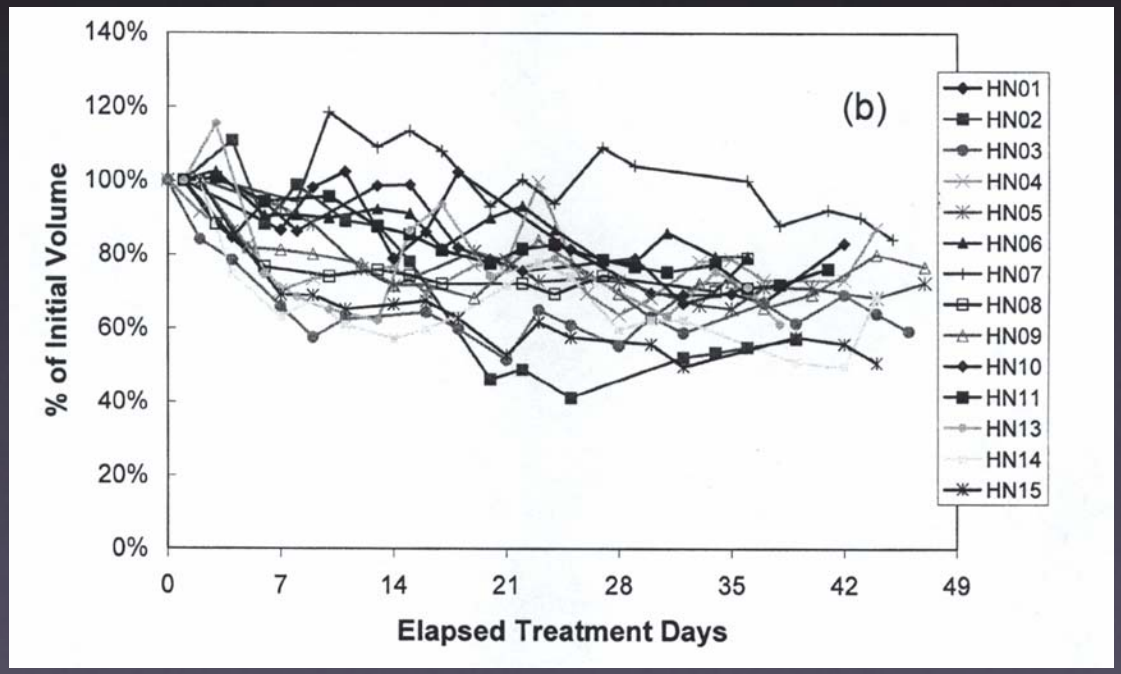
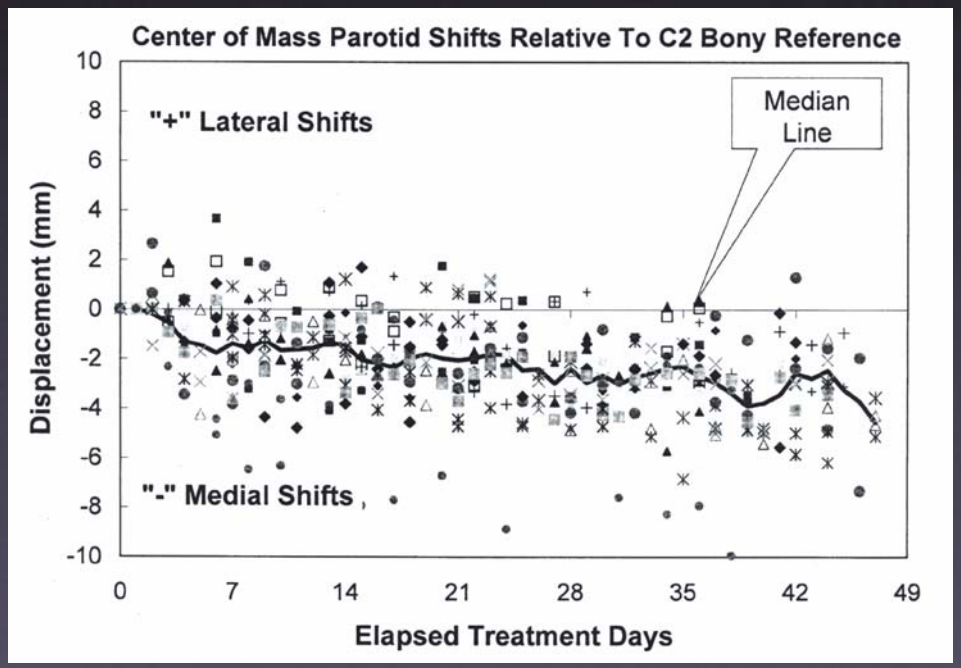
Barker *et al.* , IJROBP, 59, pp 960, 2004

Progressive deformation

Barker (2004): 14 H+N patients, 13-20 repeat CT, in-room CT

Observation of parotid shrinkage and migration





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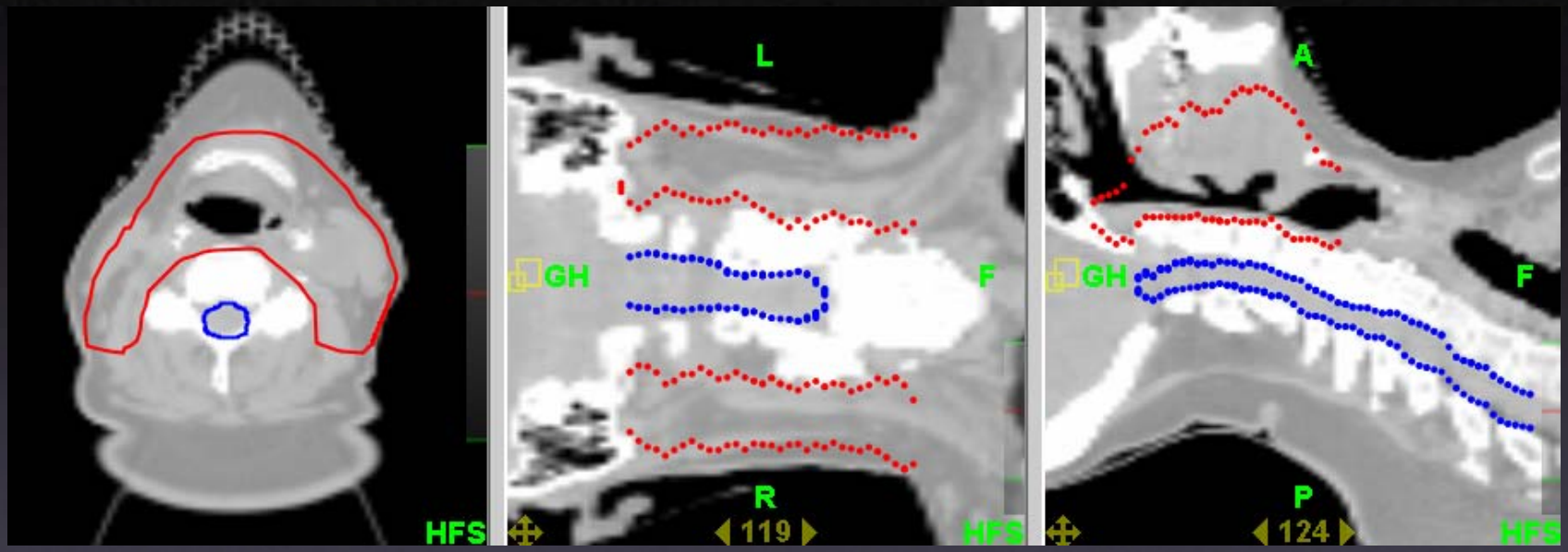
Barker *et al.* , IJROBP, 59, pp 960, 2004

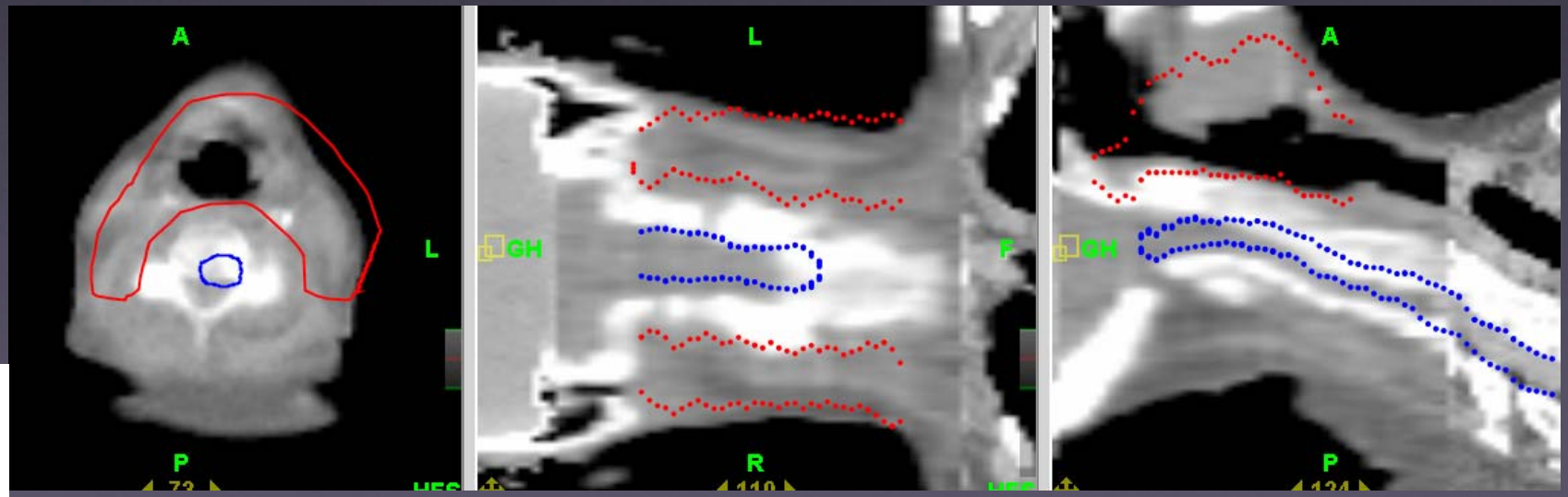
kVCT vs. end-of-treatment MVCT
Dosimetric consequence ?

kVCT:

PTV

SC





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Adaptive Radiation Therapy with the TomoTherapy system

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Terminology

Adaptive Radiation Therapy (**ART**):

Use information from images to change subsequent treatments

-Change margin based on observed setup/organ motion
-Use images to evaluate dosimetry (dose-guided, dose compensation…)

Adaptive Radiation Therapy (**ART**) with TomoTherapy:

Using MVCT images to evaluate dosimetry on daily basis

Adaptive Radiation Therapy:

need accurate HU numbers

Acquire MVCT

↓

Recalculate dose distribution on MVCT

↓

Add dose distribution to calculate cumulative dose

↓

Compare with plan

↓

Adapt plan

need deformable image registration

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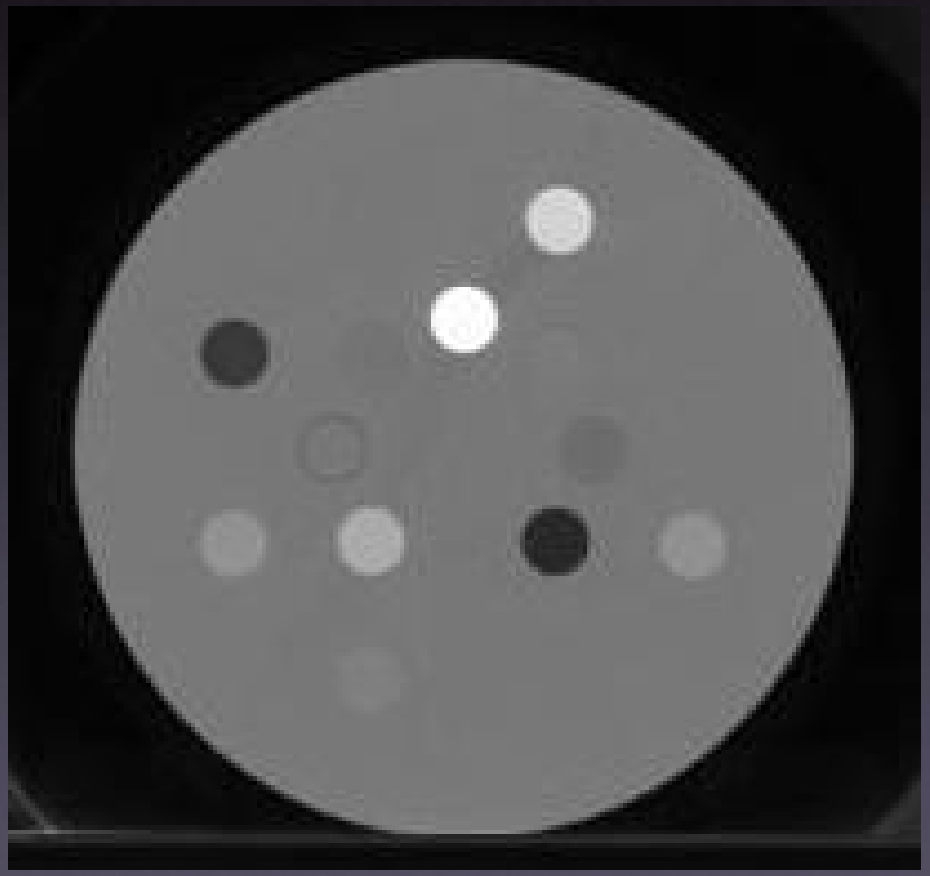
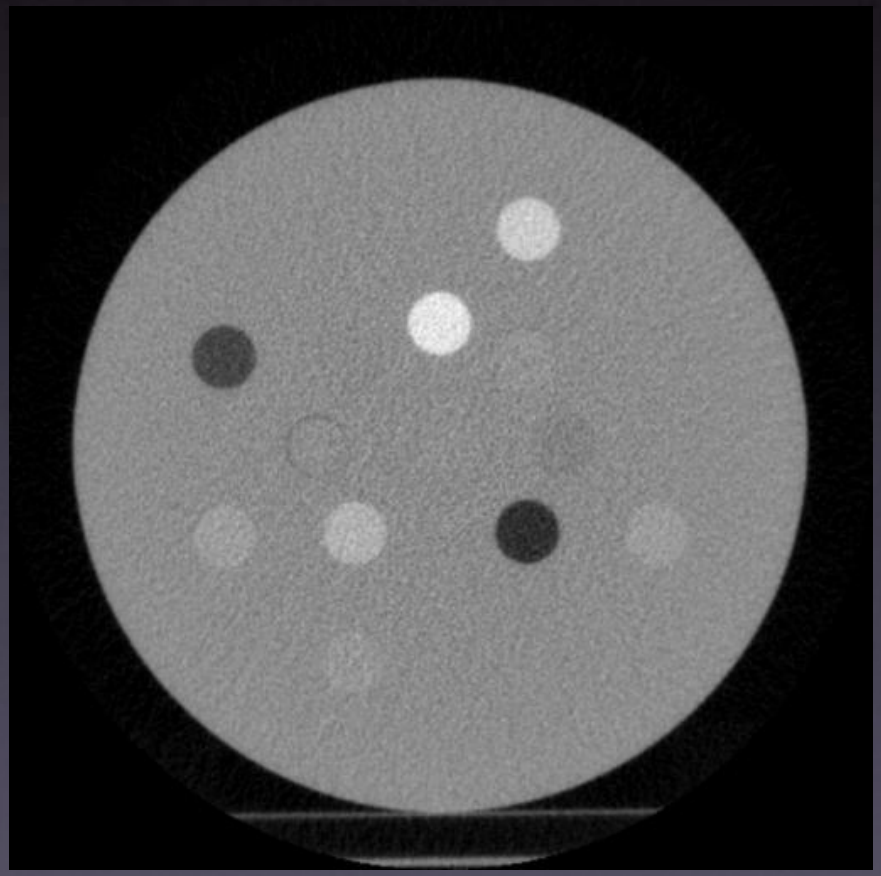
Accuracy of MVCT numbers

Need MVCT to electron density calibration

kVCT



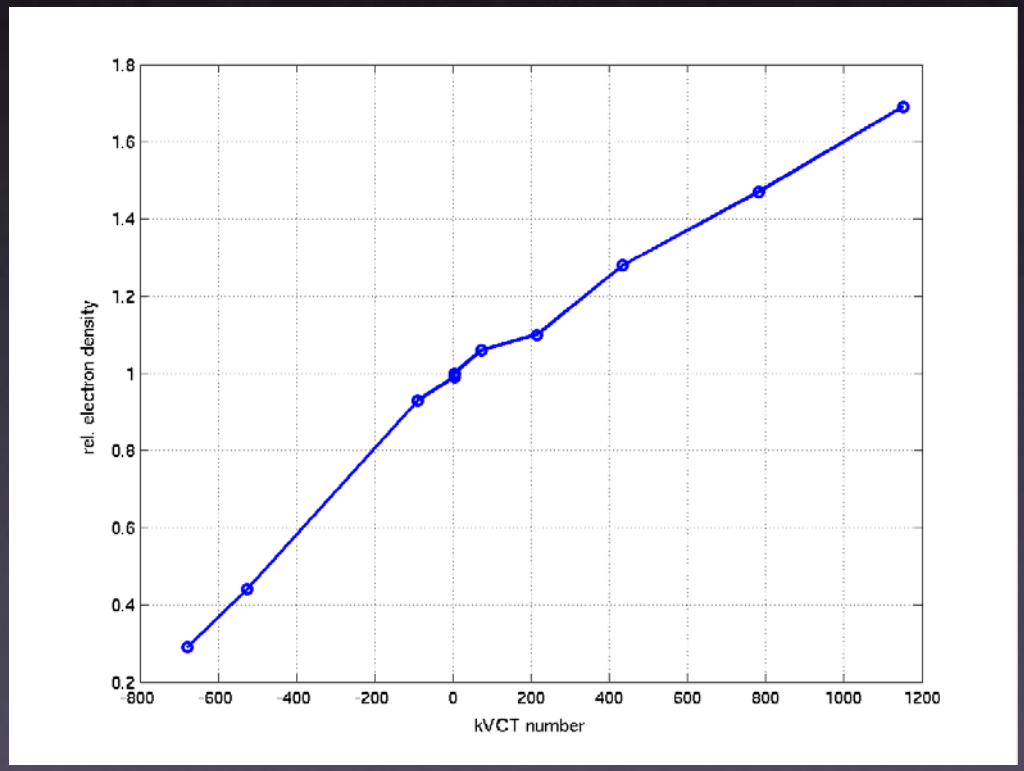
MVCT



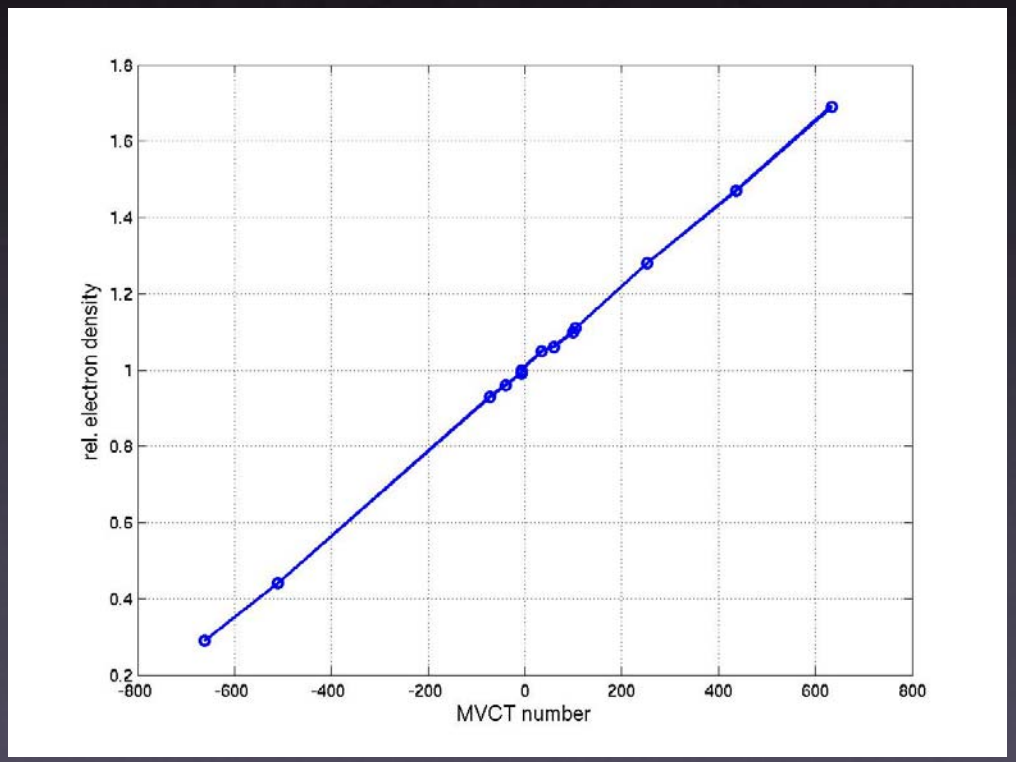
RMI, Model 467, CT to electron density phantom

MVCT to electron density calibration curves

kVCT



MVCT



MVCT Integrity ?

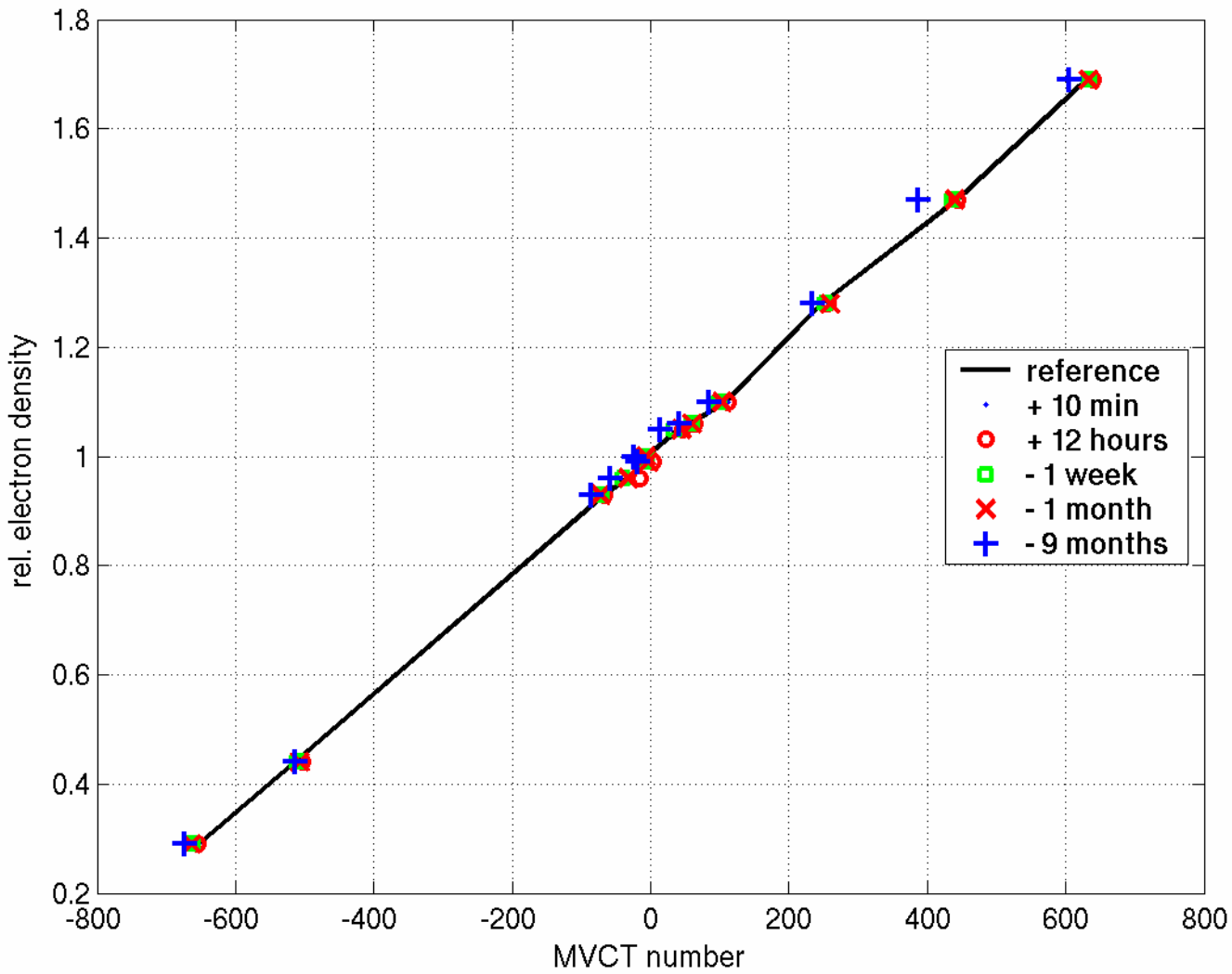
Does the calibration change with time ?

Does calibration change with phantom arrangement ?

Does the calibration change with MVCT pitch ?

MVCT Integrity ?

Does the calibration change with time ?



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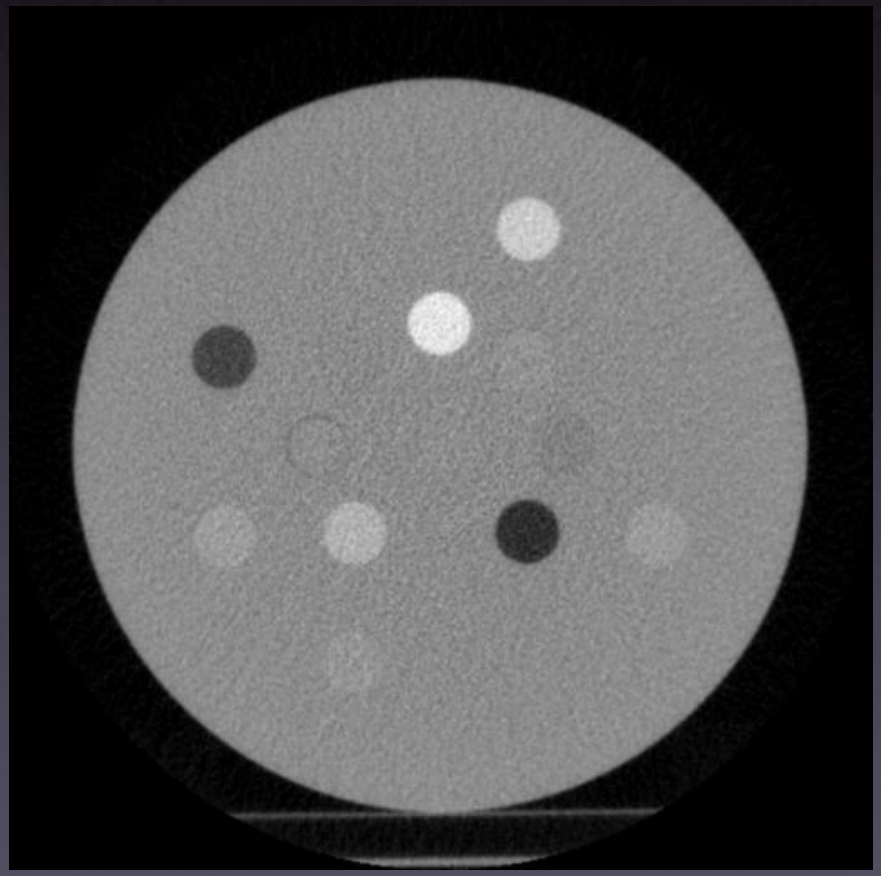
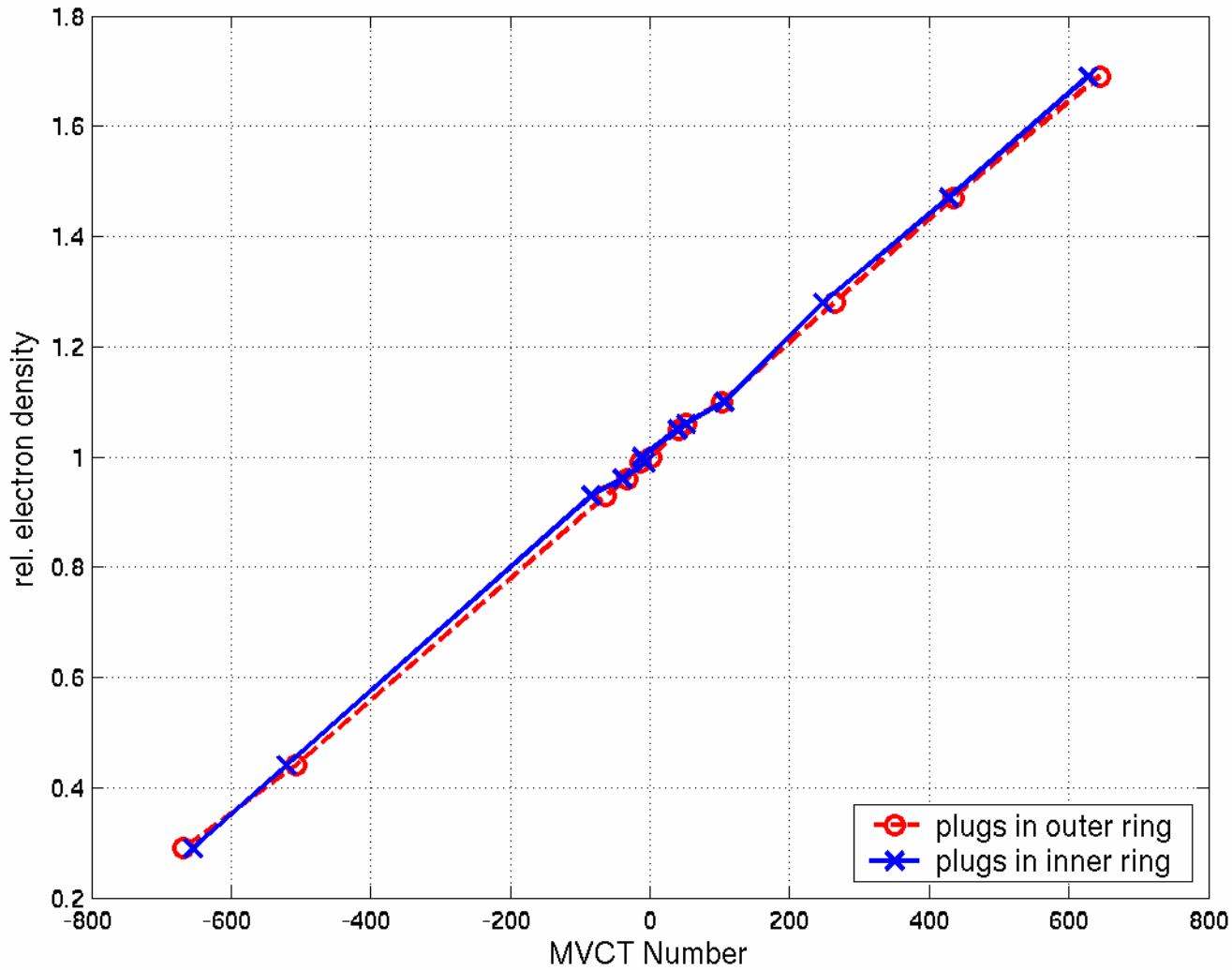
MVCT Integrity ?

Does the calibration change with phantom arrangement ?



MVCT Integrity ?

Does the calibration change with phantom arrangement ?



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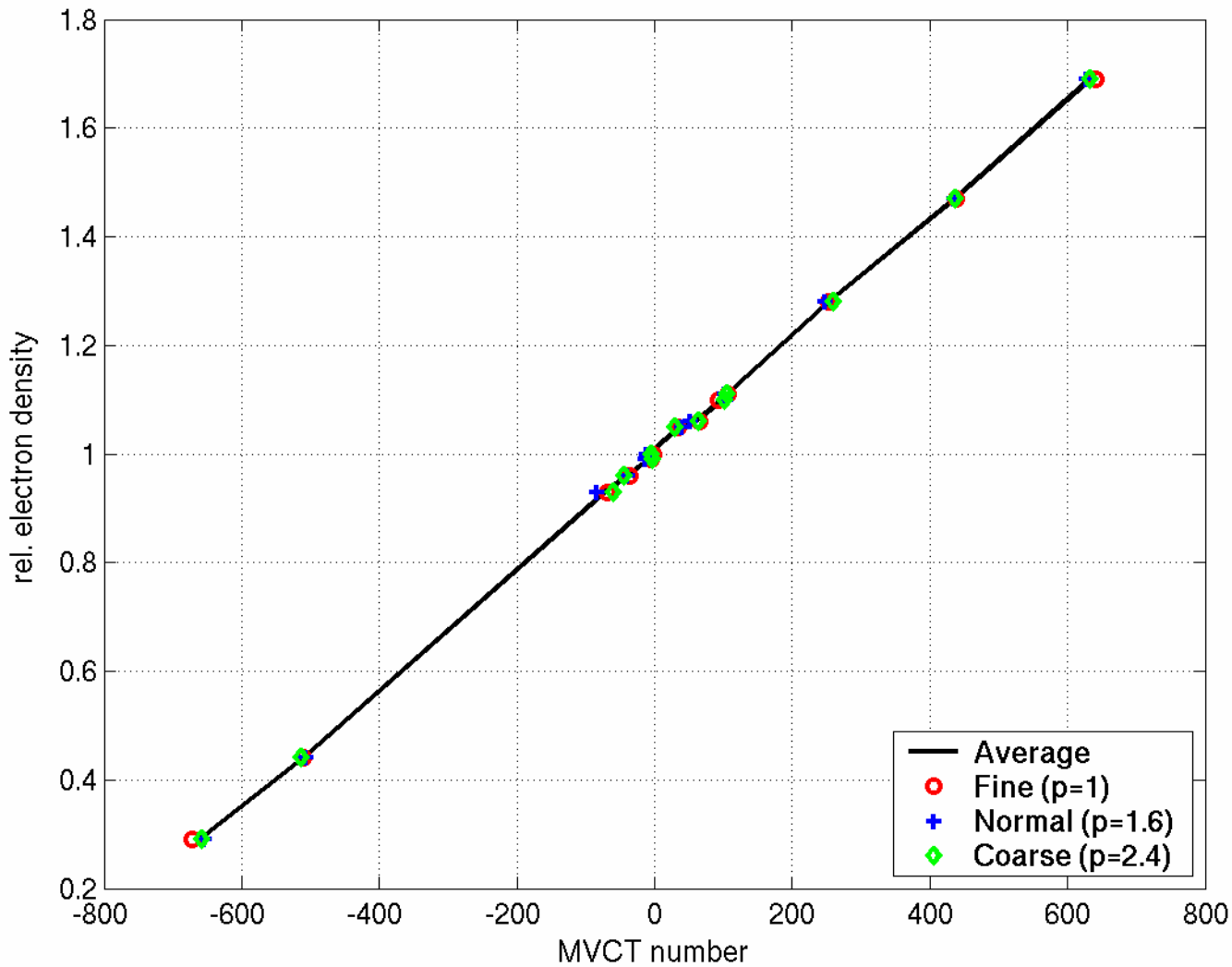
MVCT Integrity ?

Does the calibration change with MVCT pitch ?



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Dose re-computation end-to-end tests

Rigid phantom

↓

kVCT scan

↓

Fictitious target

↓

Generate treatment plan

↓

MVCT scan phantom

↓

Re-calculate dose in MVCT

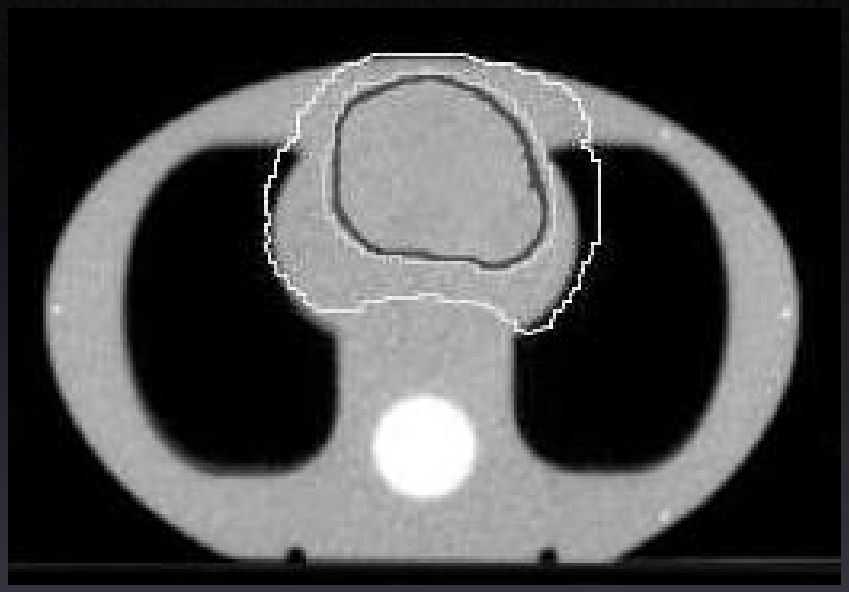
↓

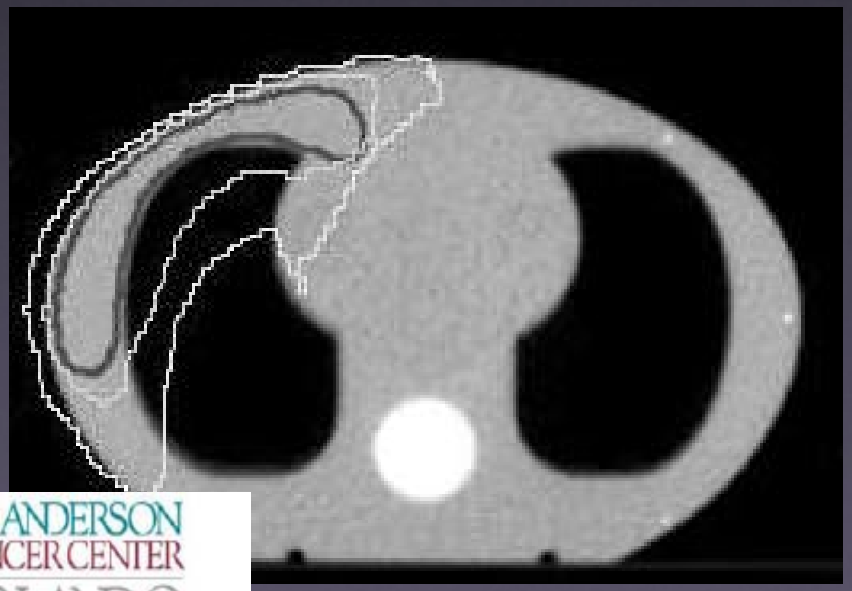
Compare plan DVH with recalculated DVH

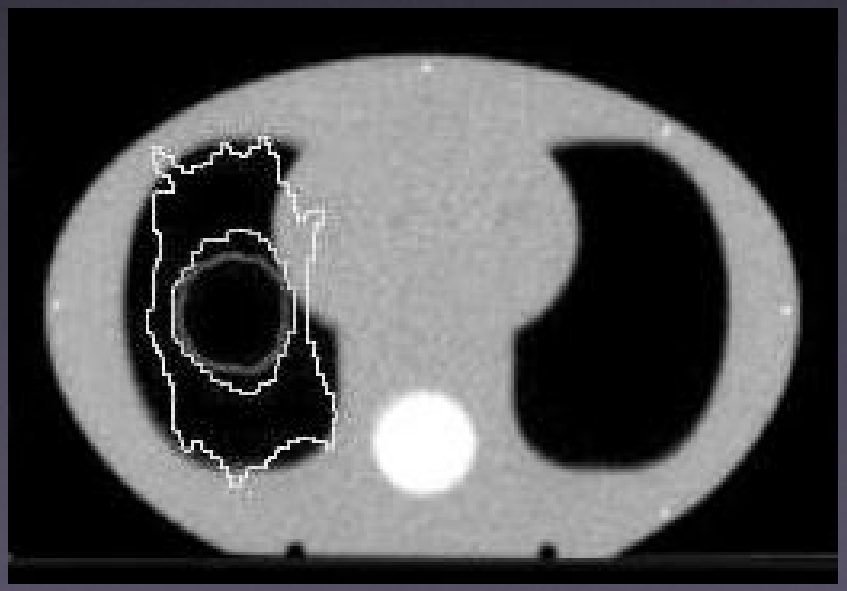
↓

Expect agreement !!!

Dose re-computation end-to-end tests







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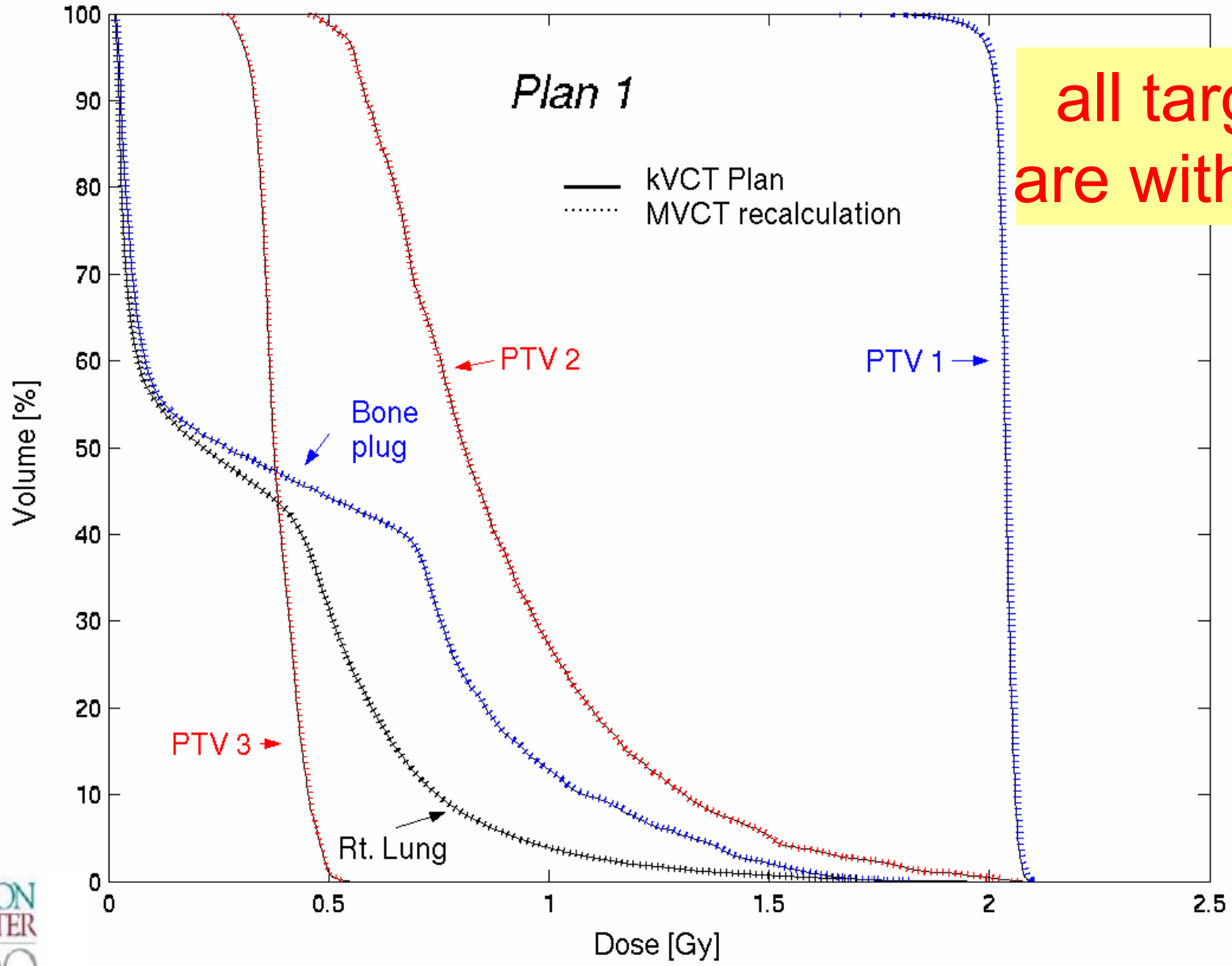
Dose re-computation end-to-end tests



all target D_{95} are within 0.5 %

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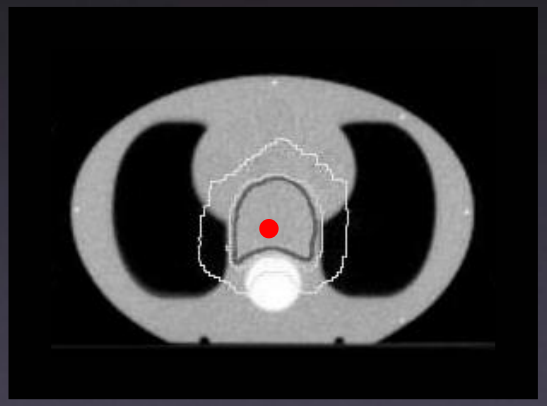
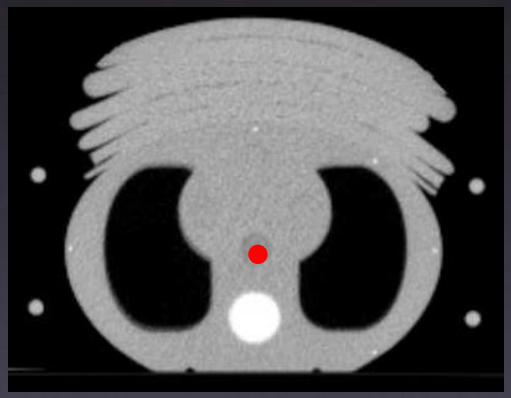
Dose re-computation end-to-end tests

Deformed anatomy ?



Plan 2

Plan 2,
Deformation 1



Plan 2,
Deformation 2

- Point of ion chamber measurement

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Dose re-computation end-to-end tests

	Meas. Diff (%)	Re-calc. Diff (%)
Plan 1, Def 1	+ 2.7	+2.9
Plan 1, Def 2	-10.5	-9.3
Plan 2, Def 1	+3.3	+3.2
Plan 1, Def 2	-11.5	-10.8

Conclusions

- MVCT numbers are reproducible

MVCT to electron density calibration is reliable

- Phantom end-to-end test results are typically

within 1 % of plan results

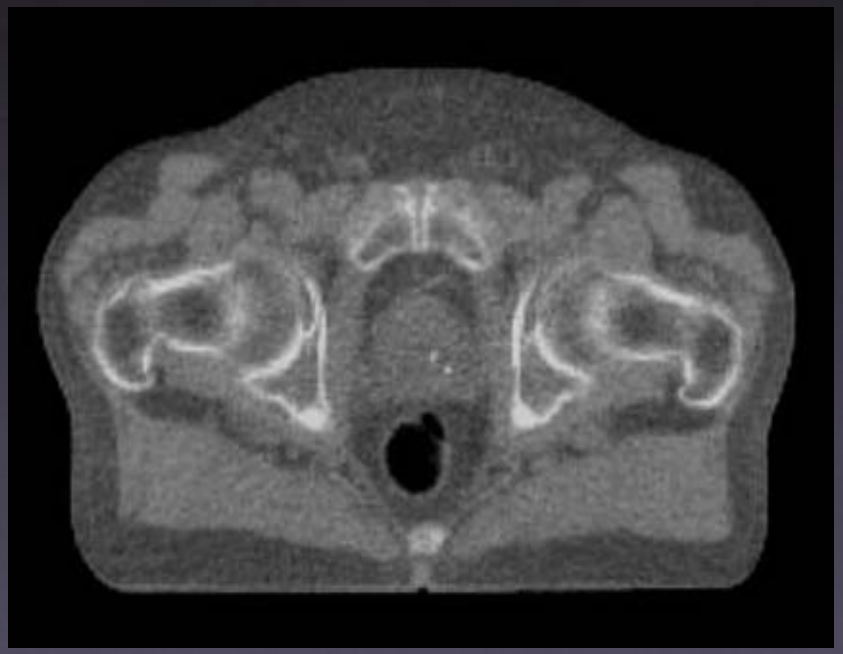
MVCT images can be used for

reliable dose computations

Langen et al.: Use of mega voltage CT (MVCT) images for dose computations. PMB, 50, pp 4259

Daily-IGRT, why ART ?

Deformation in the Pelvis
Same patient, different days



Dosimetric consequence ?

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Evaluate dosimetric consequence:

Dose Re-calculation

Use pre-treatment MVCT

↓

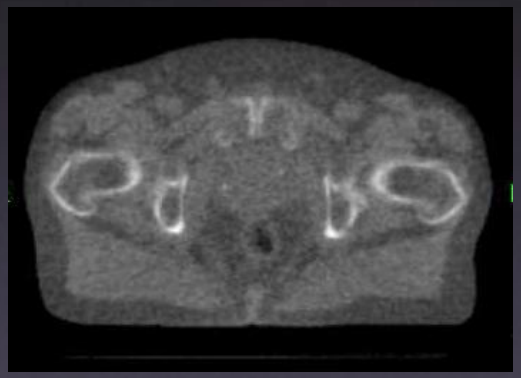
Recalculate plan based on planned MLC pattern

↓

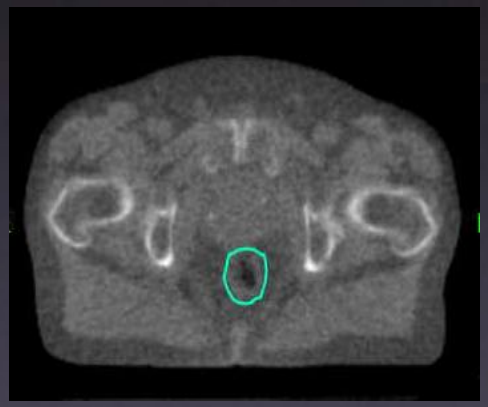
Recalculate Dose on MVCT image

Deformation in the Pelvis
Evaluate dosimetric consequence

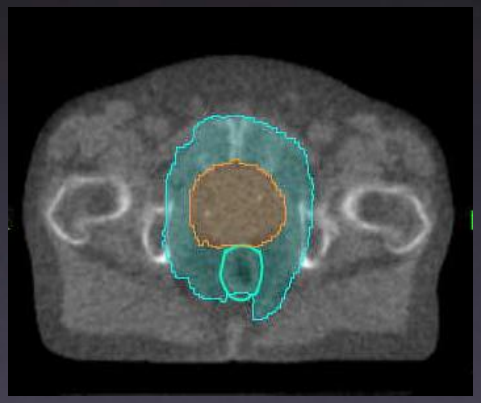
Obtain MVCT



MVCT contours



Dose recalculation



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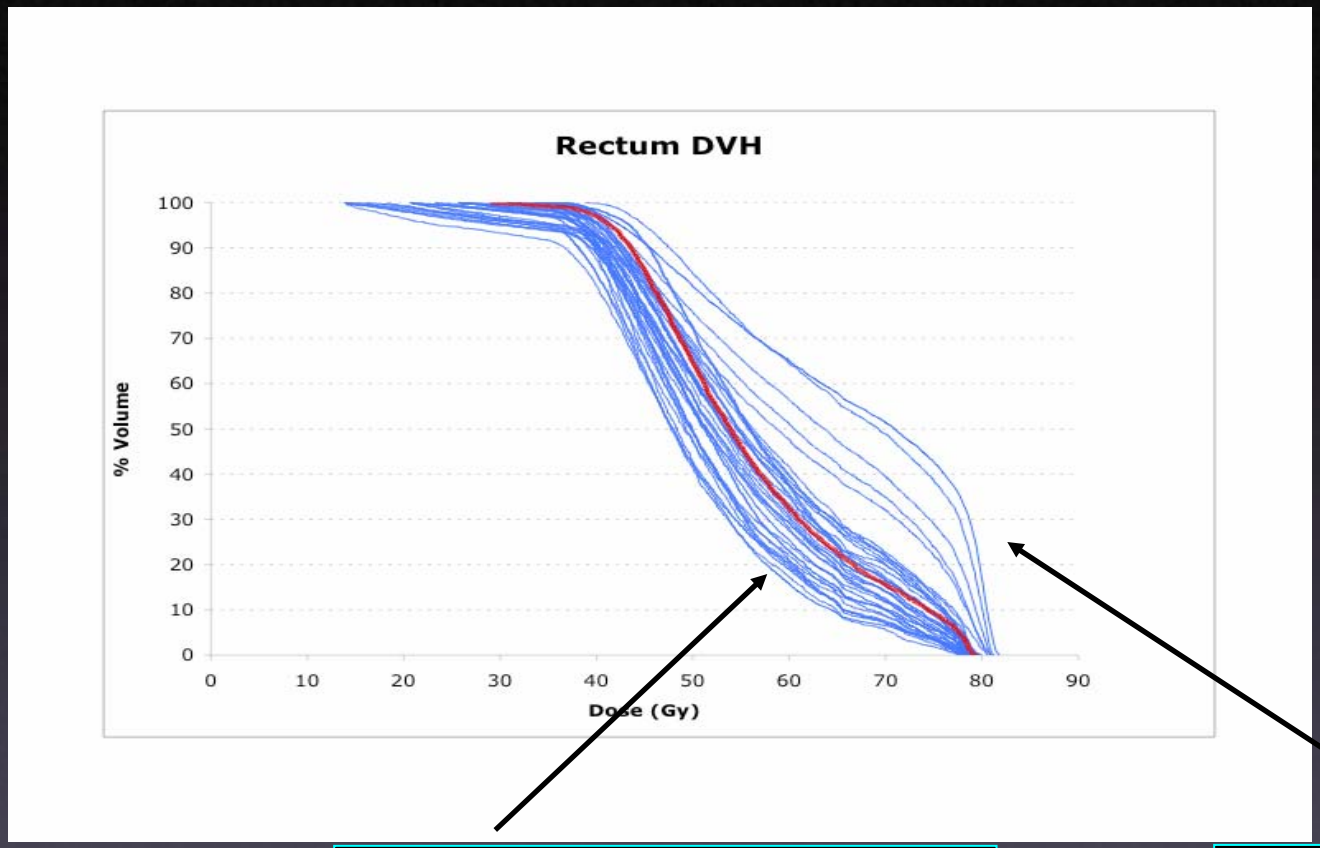
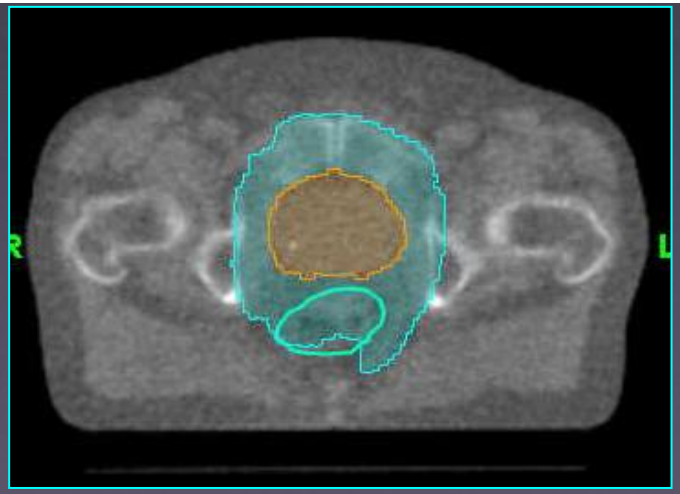
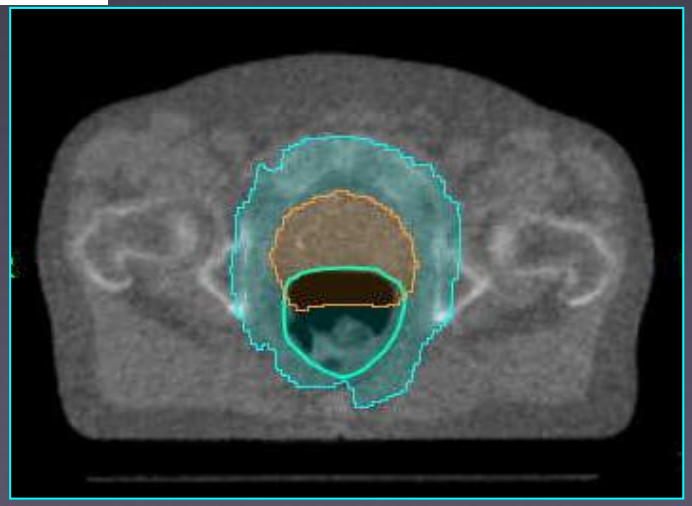
Deformation in the Pelvis



Plan DVH

39 “true” DVHs





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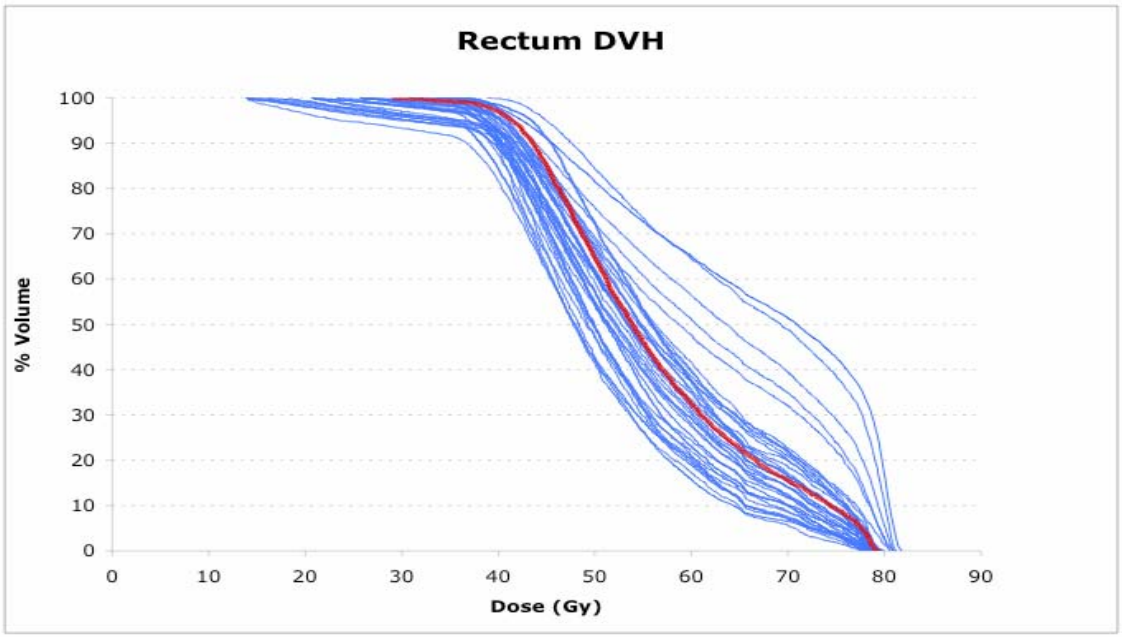
Deformation in the Pelvis



Plan DVH

39 “true” DVHs

1) Requires manual contouring
2) Need deformable image registration to calculated the cumulative DVH

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Deformable image registration

Relate voxel location x to its location in the second image (at a later time t) using a displacement vector u(x,t)

$x'(x,t)=x+u(x,t)$

Algorithm minimizes $\sum u$ and differences in HU units

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Lu *et al*. , Phys Med Biol, 49, pp 3067, 2004

MVCT to kVCT deformable image registration

Algorithm requires same HU for same voxel in MVCT and kVCT

MVCT are noisier
=> apply edge-preserving smoothing

=> MVCT numbers ≠ kVCT numbers
intensity histogram calibration

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Lu *et al*. , Phys Med Biol, submitted, 2006

MVCT to kVCT deformable image registration

Algorithm maps each MVCT voxel to kVCT

Algorithm can map each kVCT voxel to MVCT
$\Rightarrow$ can be used for automatic contouring of MVCT

$\Rightarrow$ automatically generated MVCT contours can be used to visualize deformation map

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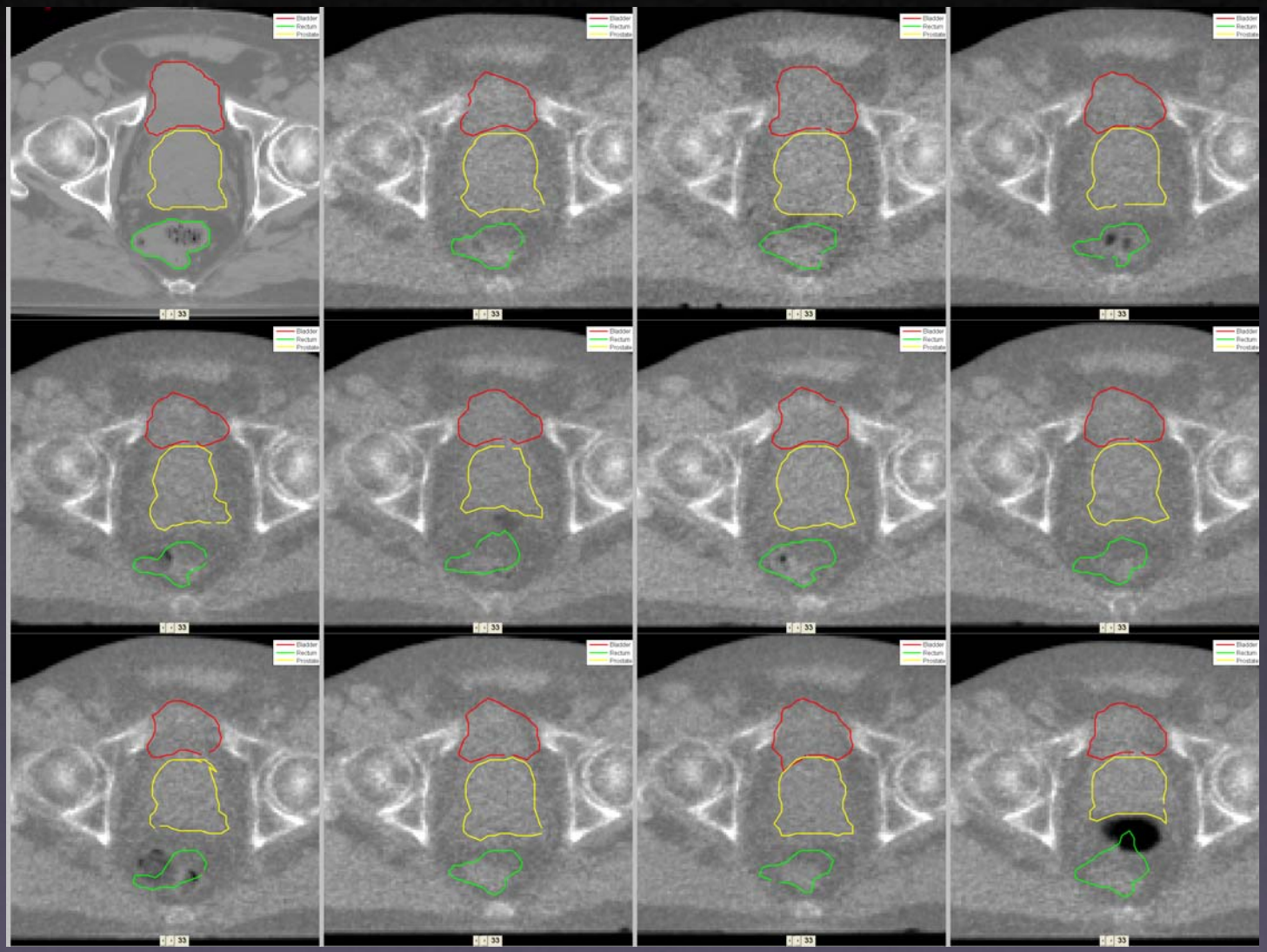
Lu *et al*. , Phys Med Biol, submitted, 2006

MVCT to kVCT deformable image registration



Lu *et al*. , Phys Med Biol, submitted, 2006

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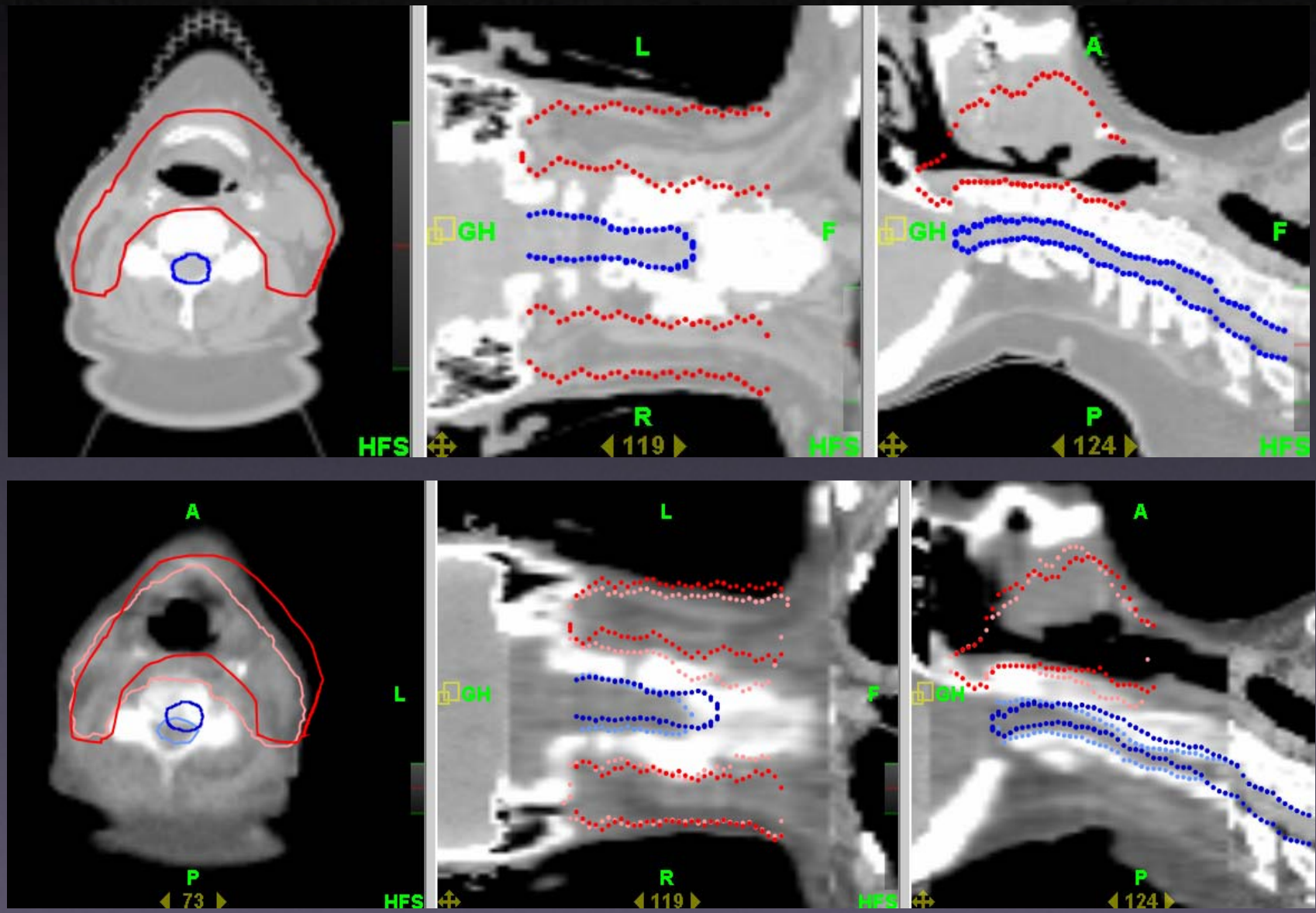
MVCT to kVCT deformable image registration

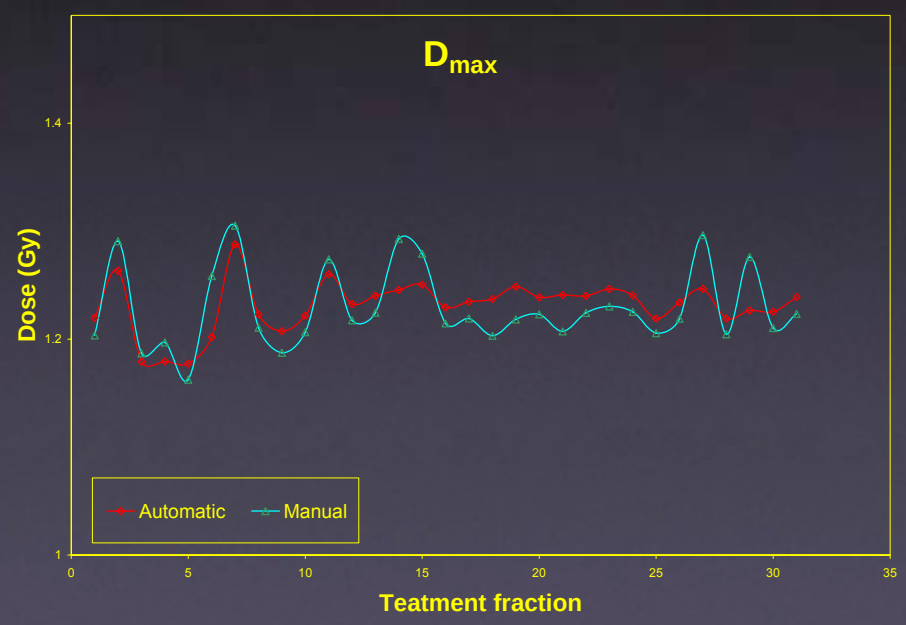
kVCT:
PTV
SC

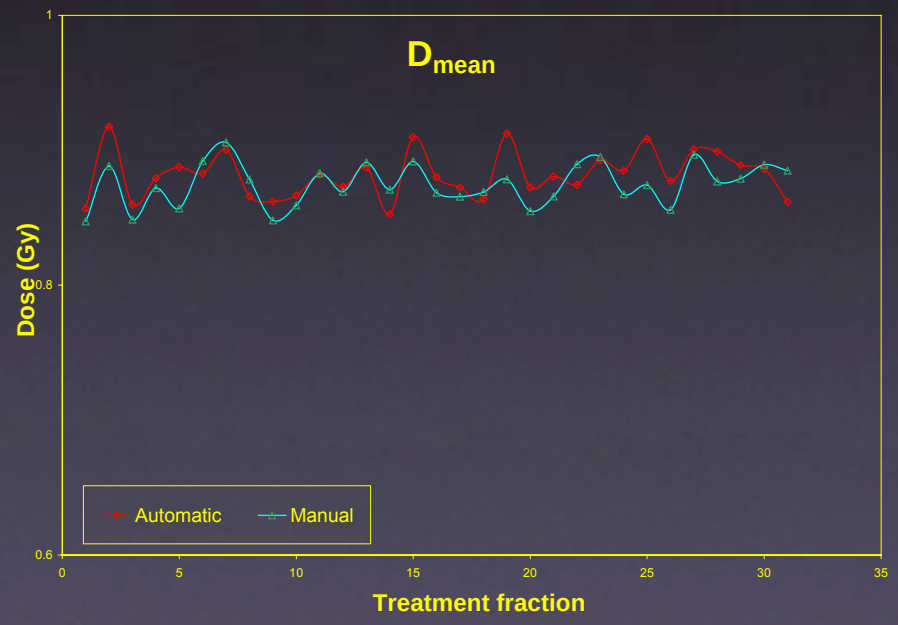
MVCT:
PTV
SC



Accuracy of automatic H+N MVCT contours ?

Spinal Cord: Automatic vs. manual contours,
Compare dose-based end points: D_{max}, D_{mean}



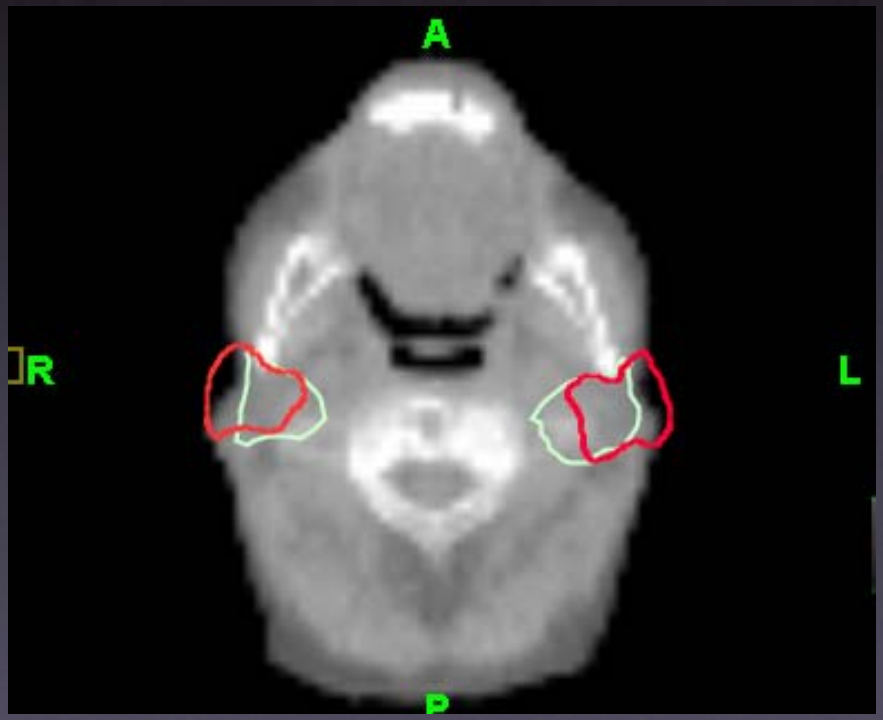


3 patients: D_{max} ratio: 1.1 ± 3.5 % D_{mean} ratio: 0.1 ± 2.5 %

Moderated Poster: AAPM 06, Langen et al.

Accuracy of automatic H+N MVCT contours ?

Parotids: Visual inspection of automatic contours



kVCT contours:

MVCT contours:

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Accuracy of automatic H+N MVCT contours ?

Parotids: Visual inspection of automatic contours

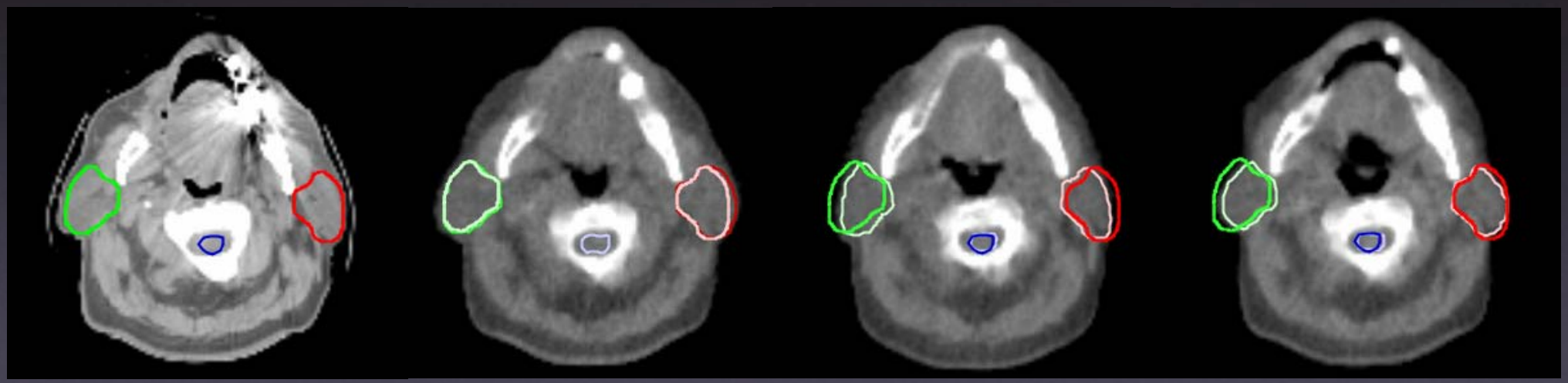
- 6 patients, 150 MVCT scans, 2 physician

<u>Conclusion:</u> The parotid contours generated by the deformable algorithm correlate with the location of these structures on the daily MVCT images.

Submitted to ASTRO 06, Manon *et al*.

Automatic MVCT contouring

kVCT Tx 1 Tx 7 Tx 15



kVCT contours:

MVCT contours:

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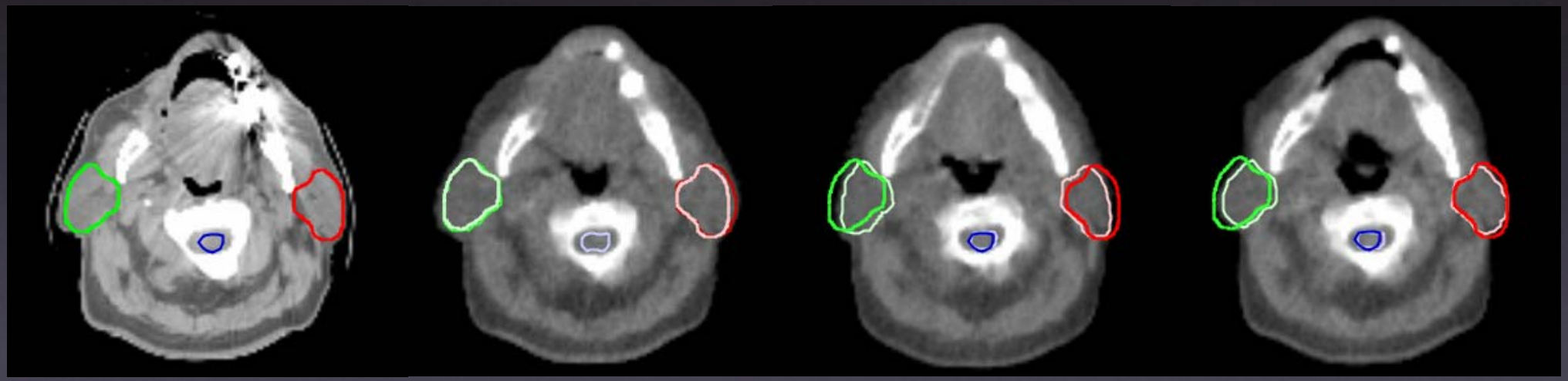
Automatic MVCT contouring

kVCT Tx 1 Tx 7 Tx 15



Dosimetric consequence ?

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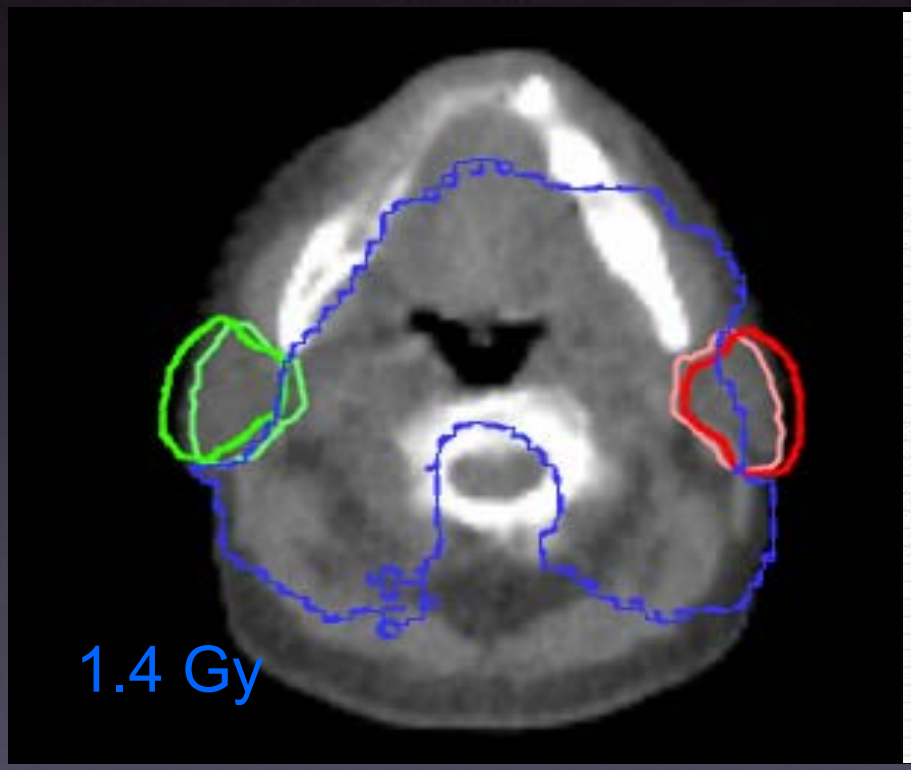
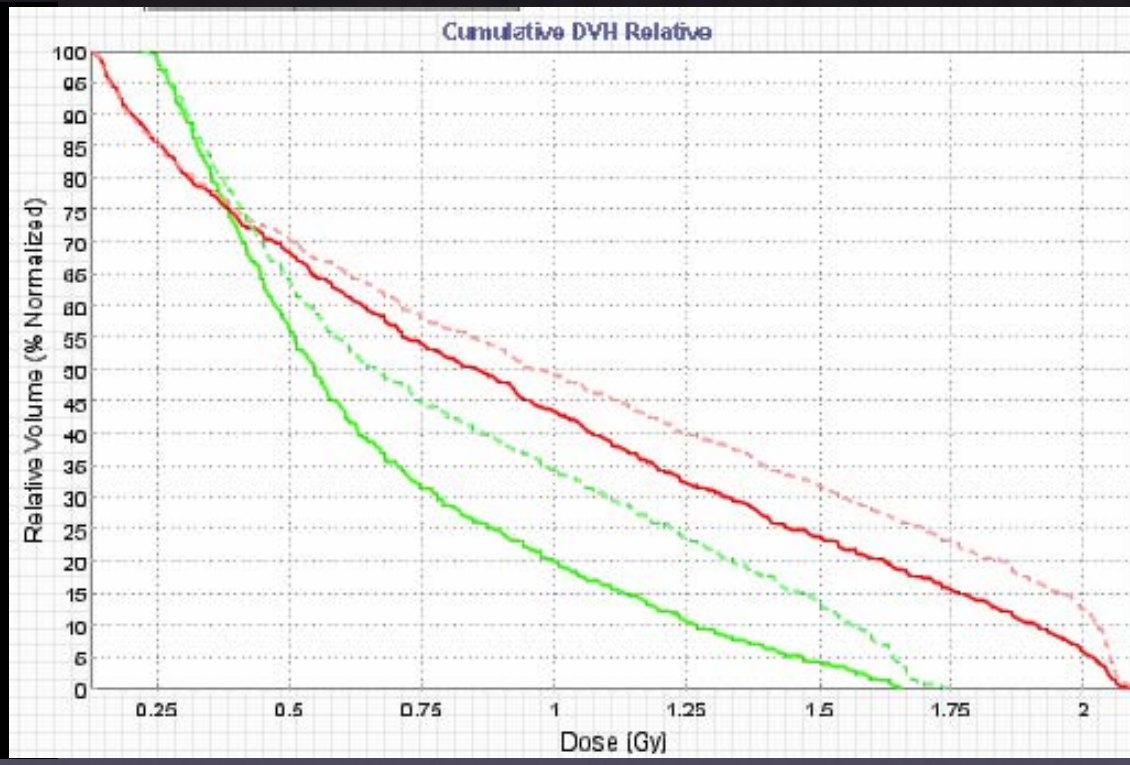
Dosimetric consequence

Tx 7



DVH



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Parotid dose during treatment course

Numerical Analysis:

-6 patients, 150 MVCT scans

<u>Conclusion:</u>
At end of treatment: mean parotid dose was on average 7.5 Gy higher than planned
Range:1.6-16.4 Gy

Submitted to ASTRO 06, Manon *et al*.

Clinical example

73 year old Head and Neck patient:
PTV prescription: 70 Gy in 35 fractions

Prescription

% Vol For PTV70Gy 95.0 % will receive ..... 70.0 Gy

Stats

Field Width: 2.56 cm - Jaws(1.15,-1.05) Pitch: 0.300 Dose Calc Grid: Normal Batch beamlets

Tumor Constraints

Name	Display	Color	Blocked	Use?	Importance	Max Dose [Gy]	Max Dose Per	DVH Vol [%]	DVH Dose [Gy]	Min Dose [Gy]	Min Dose Per
LowerCord	✓		None								
UpperCord	✓		None								
PTV70Gy	✓		None	✓	300	70.0	55700	95.0	70.0	70.0	76500
PTV57Gy	✓		None	✓	100	57.0	14000	95.0	57.0	57.0	65000

Sensitive Structure Constraints

Name	Display	Color	Blocked	Use?	Importance	Max Dose [Gy]	Max Dose Pen.	DVH Vol [%]	DVH Dose [Gy]	DVH Pt. Pen.
Optic Chiasm			None							
Rt Parotid	✓		None	✓	50	57.0	80	45.0	20.0	13000
Lt Parotid	✓		None	✓	50	70.0	7000	90.0	5.0	14000
Mandible			None	✓	20	70.0	40	75.0	30.0	6000

Dose Display

Isodose

72.1
70
57
50
35

Density Image Viewer

Density Image

Optimize

Mode: Beamlet

Topo Mode

Ext Mask

Modulation Factor: 2.000

Initiate Full Dose after 20 iterations.

Start

Pause

Resume

Get Full Dose

Cancel

Dose-Volume Histogram - Cumulative Mode Relative

Relative Volume (% Normalized)

Dose (Gy)

Vol Min < 0.0 > Vol Max < 100.0 > Gy Min < 0.0 > Gy Max < 80.0 >

Patient Images

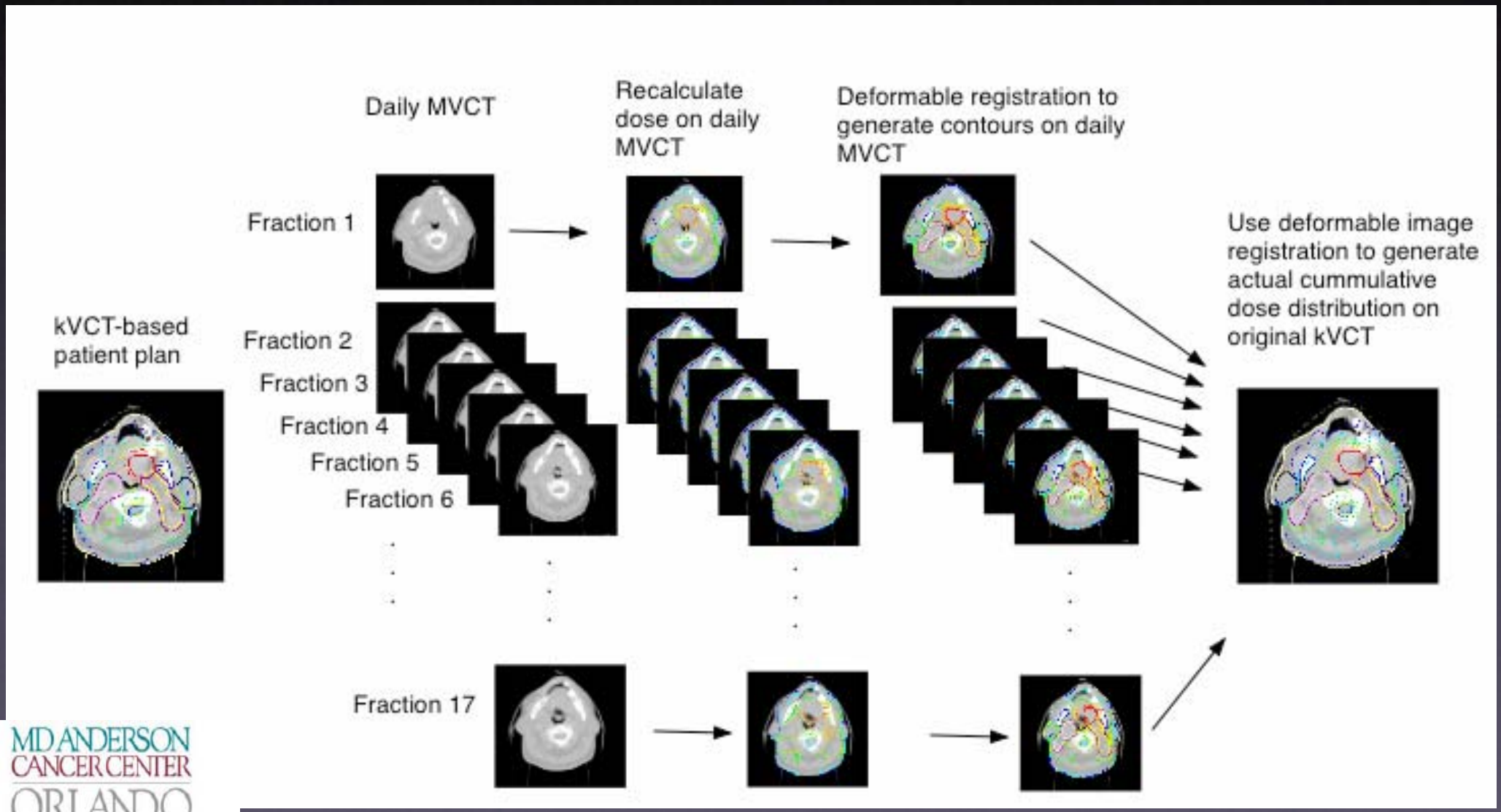
A R L P 58 HFS

L GH F R 107 HFS

A GH F P 133 HFS

Clinical example

First 17 fractions:



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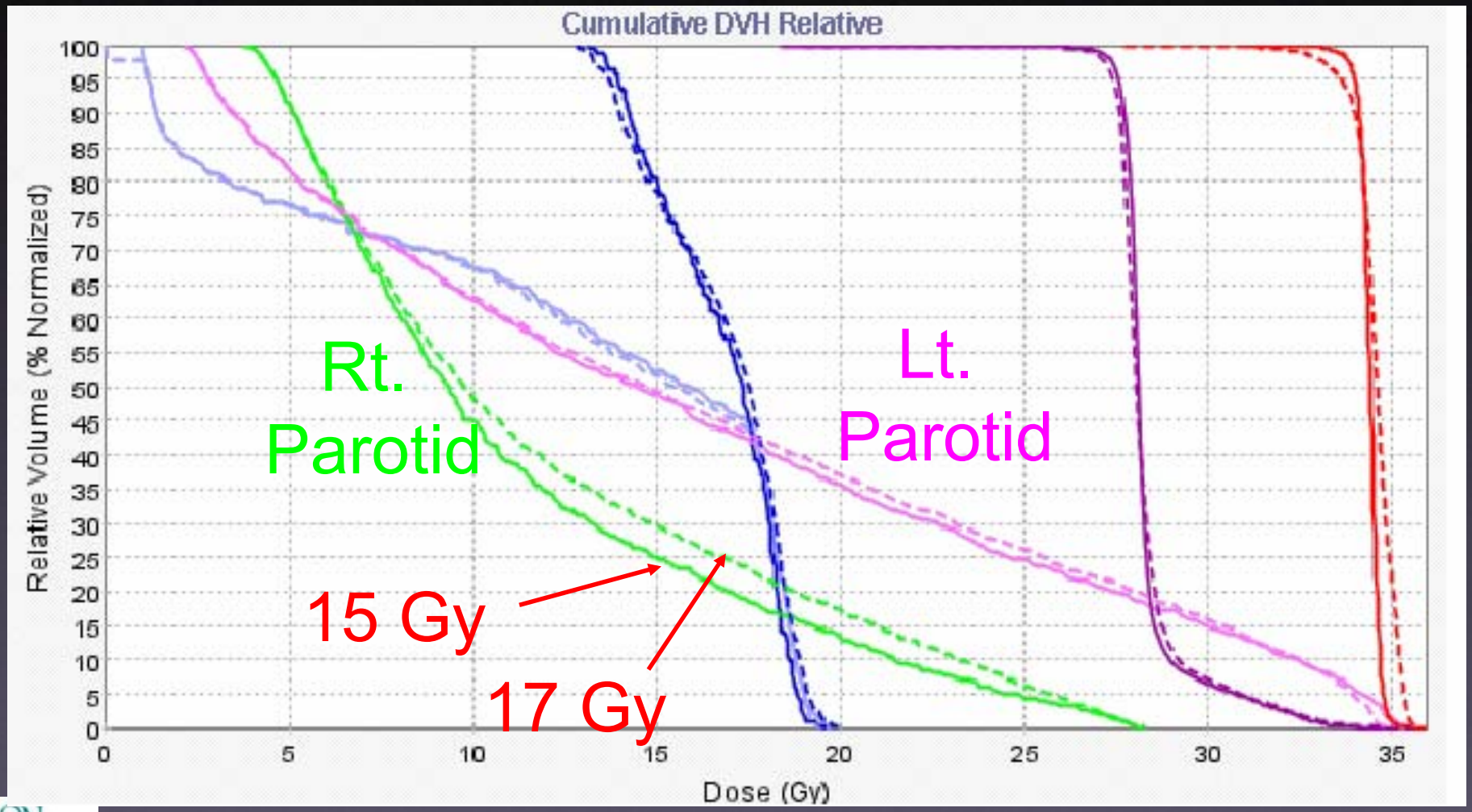
Plan vs. deformable registration DVH after 17 fractions



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Generate adaptive plan

-Obtain new kVCT scan of patient

-How to transfer dosimetry information to new kVCT ?

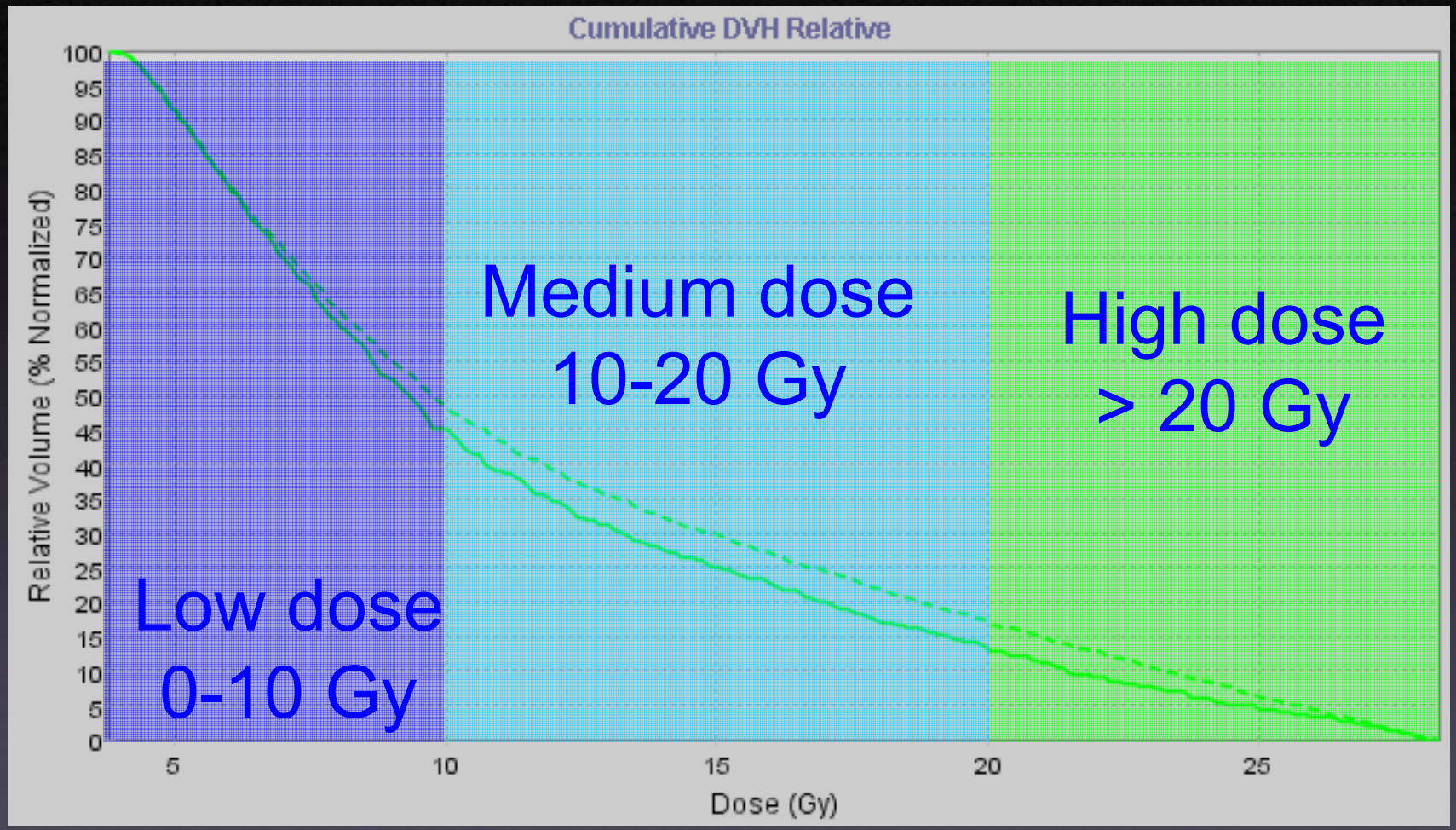
Generate adaptive plan

-Use kVCT-kVCT deformable registration to transfer original structures to second kVCT

-Physician reviewed structures

-Generate new plan ➔ Limit dose to over-dosed parotid region

Rt. Parotid DVH (after 17 Txs)



Dose difference mostly in 10-20 Gy region

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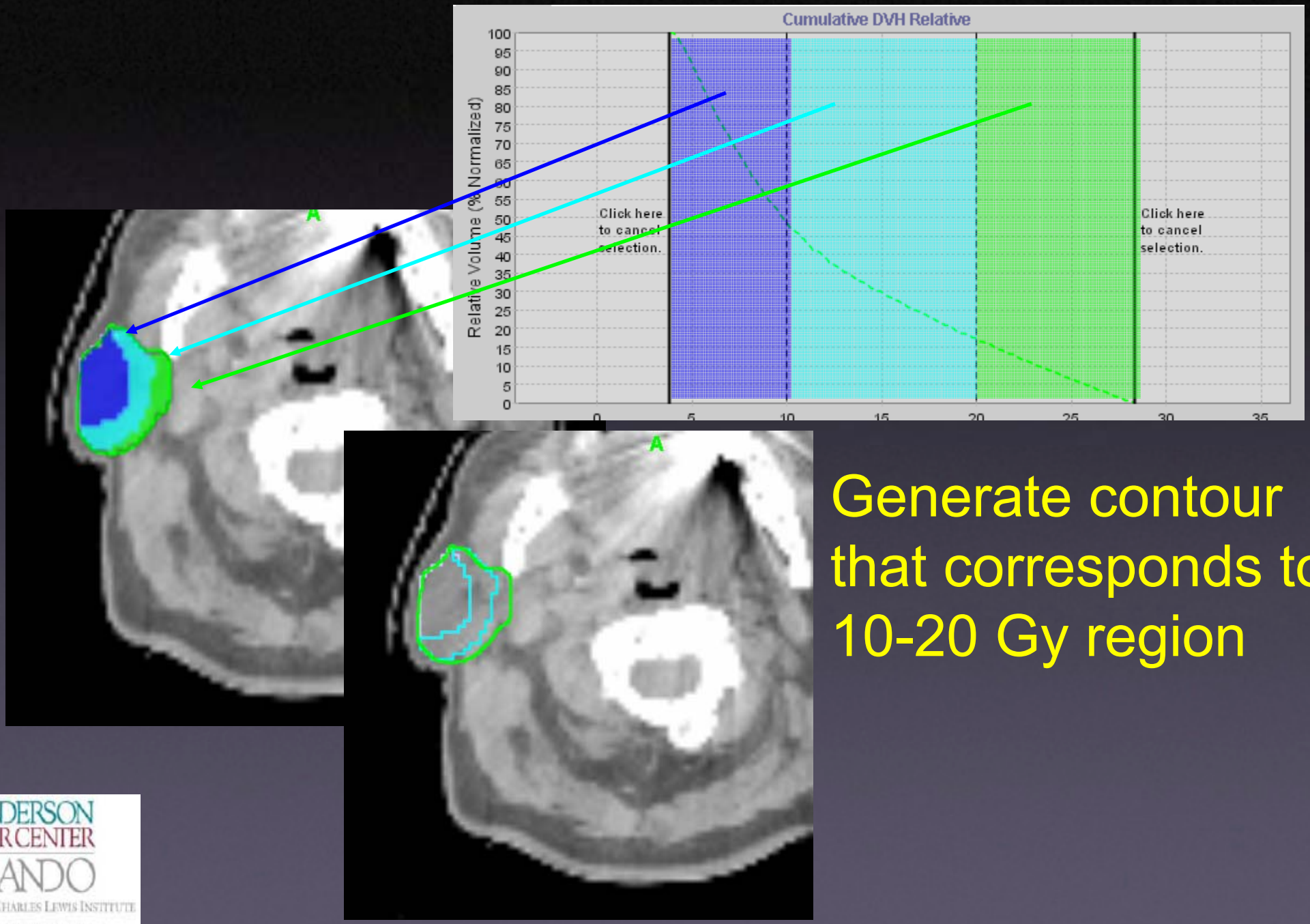
Parotid DVH



Generate contour that corresponds to 10-20 Gy region

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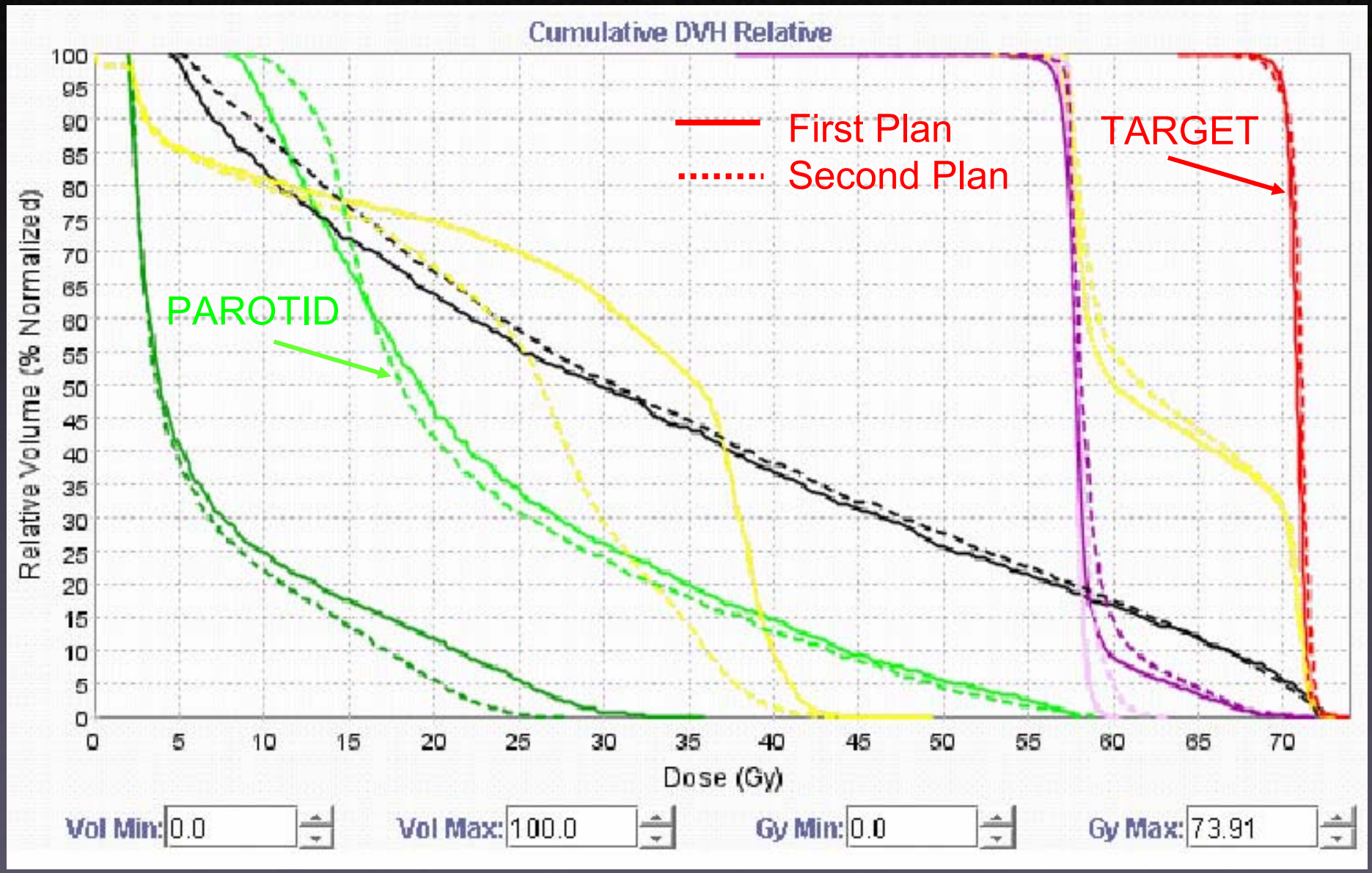
Generate second plan



Patient completes treatment

Daily scans
Daily deformable registration

FULL COURSE

WHAT IF SCENARIOS….compare

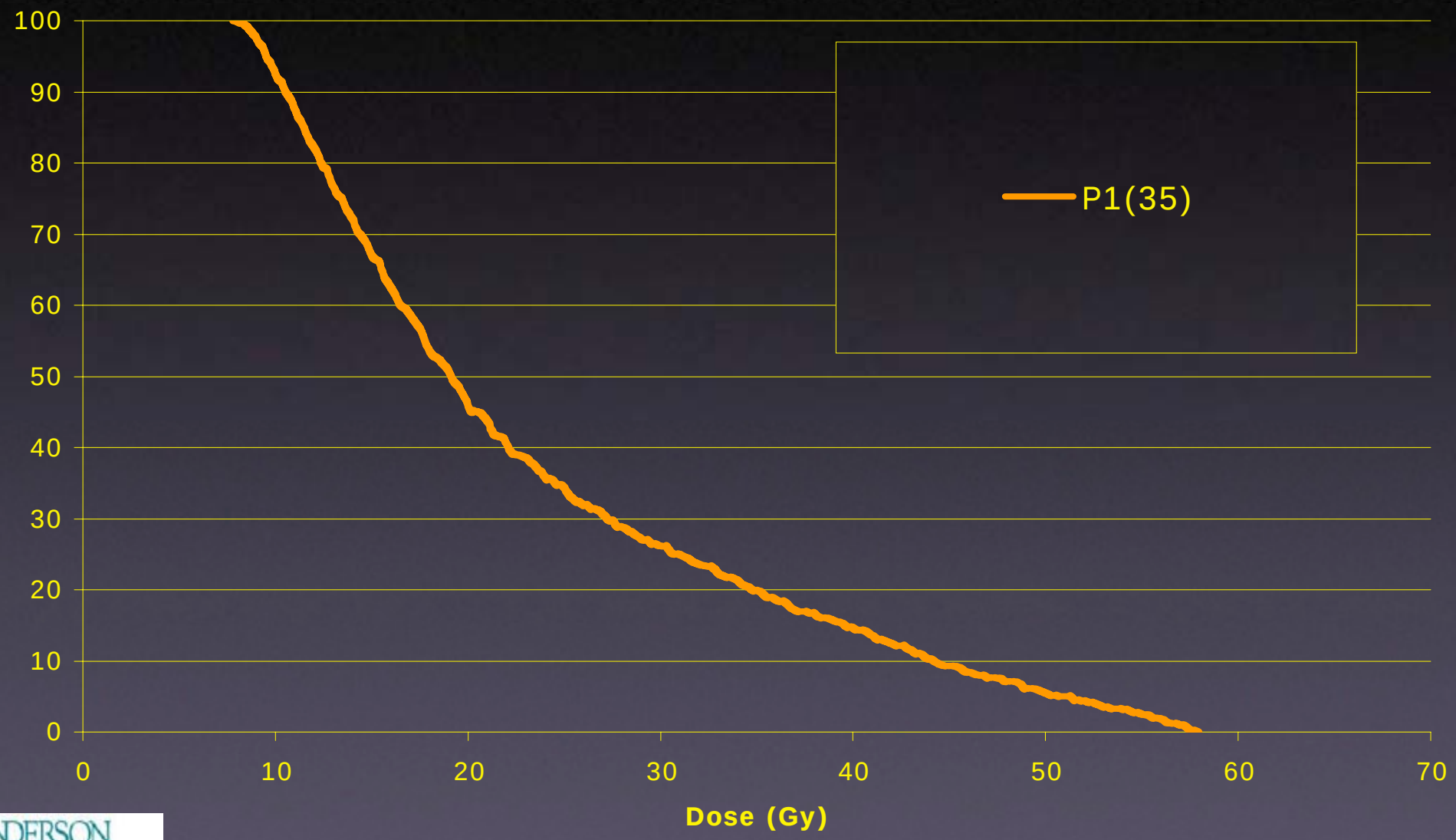
-Original Plan P1(35)

-Plan 1 delivered for 17 fx + Plan 2 for 18 fx
Planned to deliver with adaptive RT
D1(17)+P2(18)

-Actual delivery (Plan 1-17 fx and Plan 2-18 fx)
D1(17)+D2(18)

-without adaptive RT, Plan 1 only D1(35)

What if .. (Rt. Parotid DVH)



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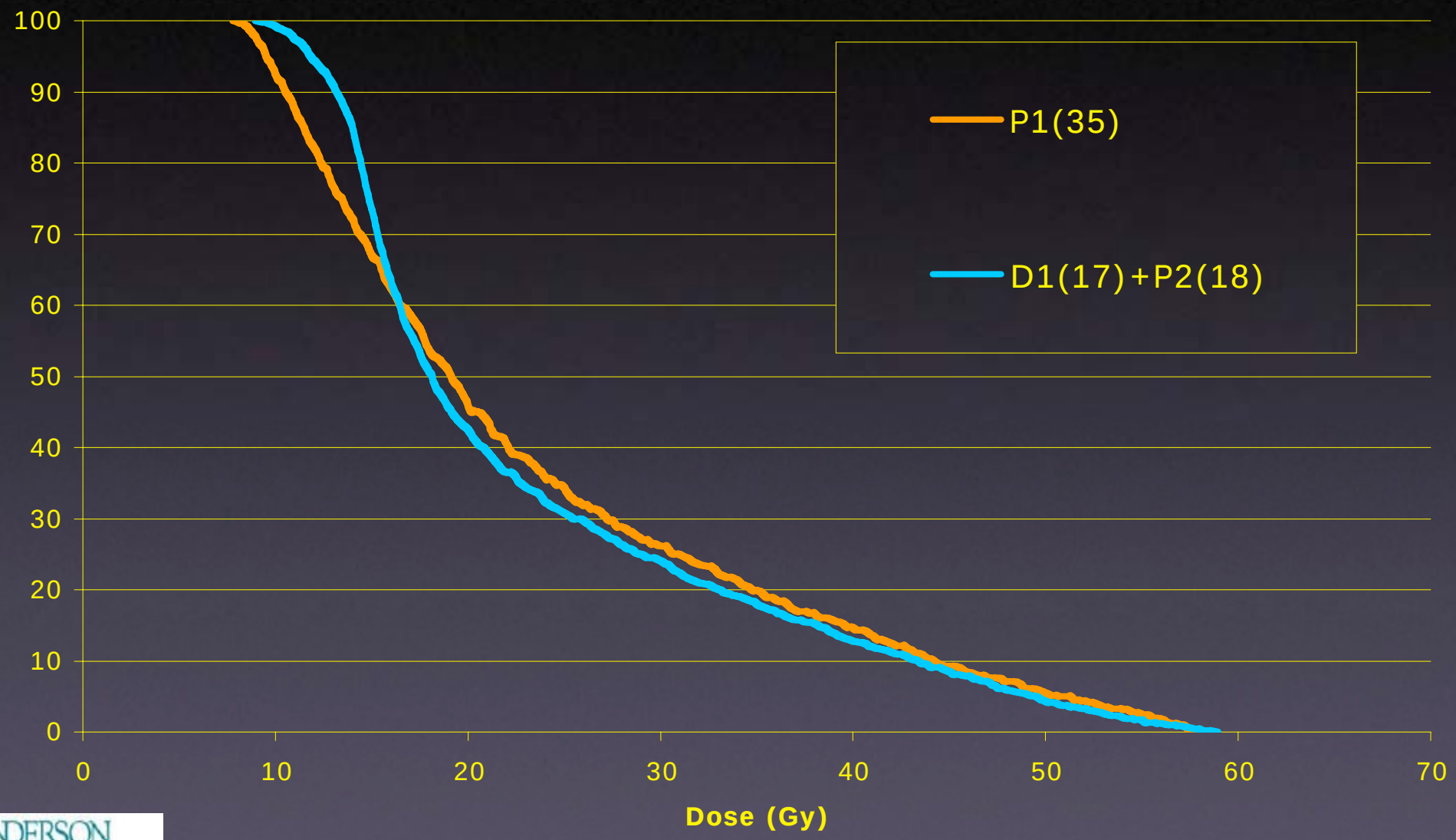
What if .. (Rt. Parotid DVH)



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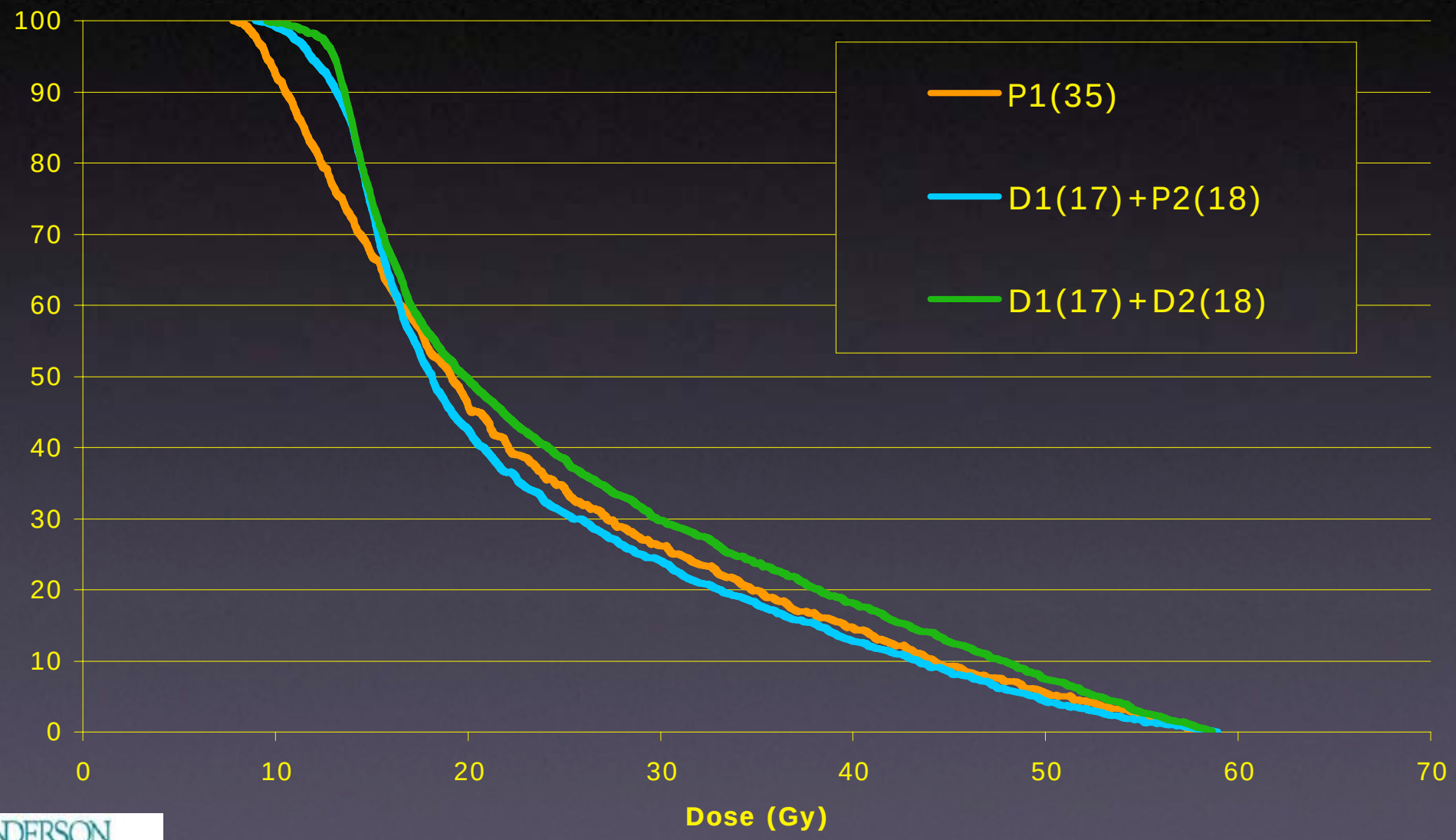
What if .. (Rt. Parotid DVH)



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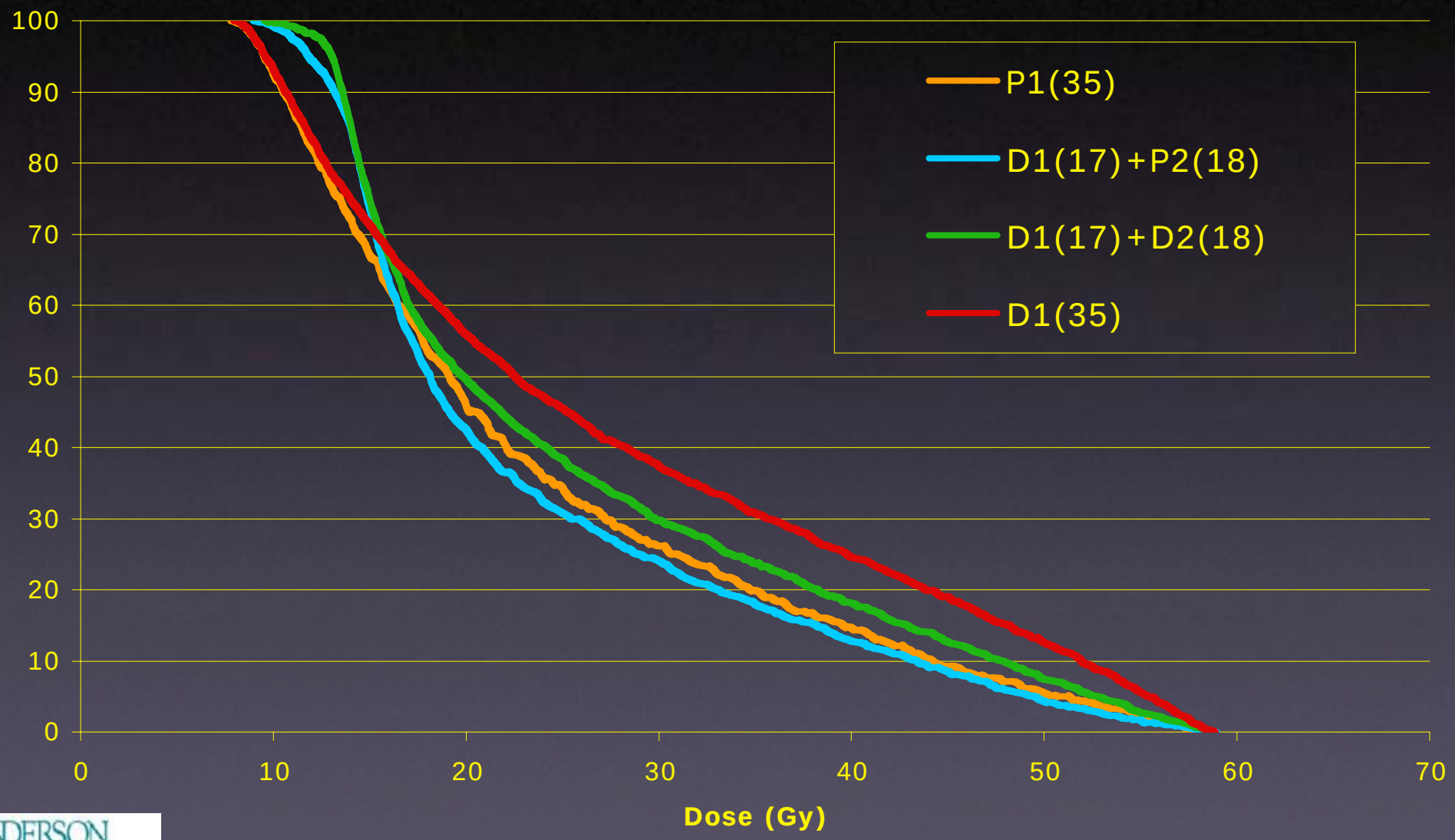
What if .. (Rt. Parotid DVH)



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Conclusion

Opportunities

- Assess consequence of deformation
- Correct differences between delivered and planned dose in adaptive Plan

Challenges

- When to adapt plan ?
- How often ?
- Verify accuracy of deformable registration
- Shrinking volumes ?

Thanks !

MD Anderson:

Sanford Meeks

Tom Wagner

Twyla Willoughby

Omar Zeidan

Amish Shah

Arati Limaye

Patrick Kupelian

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