Tomotherapy

Thomas Rockwell Mackie
Tomotherapy Research Group
Depts. Of Medical Physics, Human Oncology and Biomedical Engineering
University of Wisconsin
Madison WI 53706
Phone: (608) 262-7358
Email: trmackie@facstaff.wisc.edu
Web: www.madrad.radiology.wisc.edu

Contributors to this Talk

- Gustavo Olivera
- Paul Reckwerdt
- Jeff Kapatoes
- Ken Ruchala
- John Balog
- Richard Schmidt
- Ed Fitchard
- Dave Pearson
- Eric Schloesser
- Ray MacDonald
- Robert Jeraj
- Minesh Mehta
- Mark Ritter
- Jack Fowler
- Harry Keller
- Weiguo Lu
- Jeni Smilowitz
- Wolfgang Tomé
- Rufus Scrimger
- Lisa Forrest

Financial Disclosure

In addition to a University of Wisconsin Professor, I am a co-founder of TomoTherapy Inc. (Middleton WI) which is participating in the commercial development of helical tomotherapy.

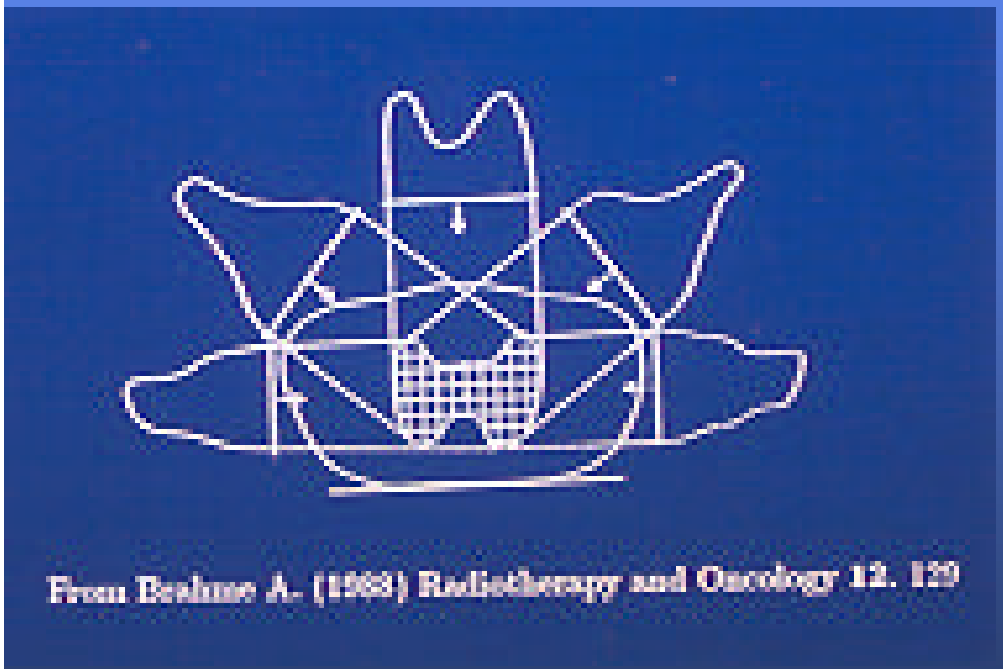
TomoTherapy's 1,400 m^2 Middleton facility.

www.tomotherapy.com

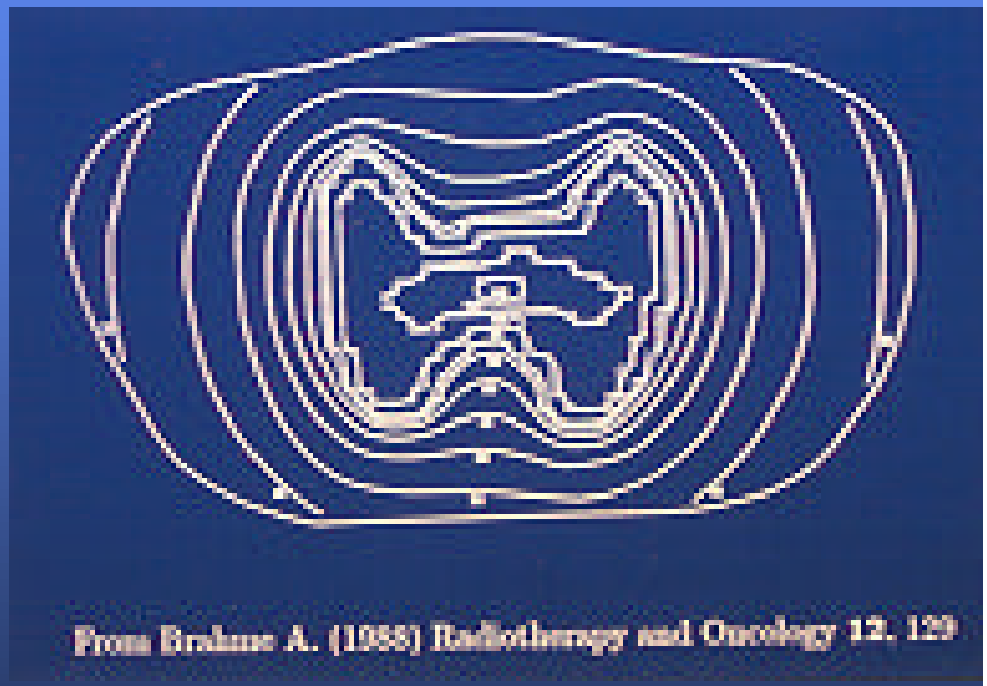
Outline

- Optimization → IMRT → Conformal Dose Distributions
- Sequential (or Serial) Tomotherapy (NOMOS Peacock™)
- Clinical Helical Tomotherapy Unit
- Dosimetry of Helical Tomotherapy
- Examples of Tomotherapy Dose Distributions
- Megavoltage Computed Tomography (MVCT)
- Adaptive Radiotherapy
- Clinical Implications

Optimization → IMRT → Conformal Dose Distributions



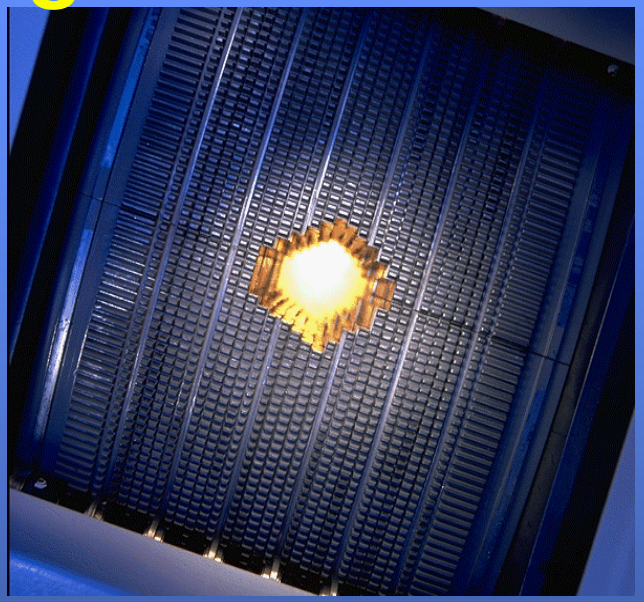
From Brahme A. (1988) Radiotherapy and Oncology 12. 129



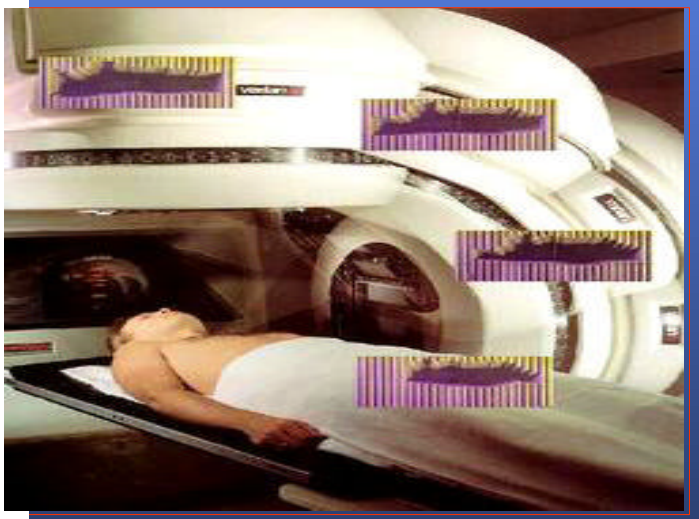
From Brahme A. (1988) Radiotherapy and Oncology 12. 129

Anders Brahme first showed that intensity modulated fields of radiation would lead to more conformal dose distributions that would spare normal tissue.

IMRT Using Conventional MLC's



Siemens

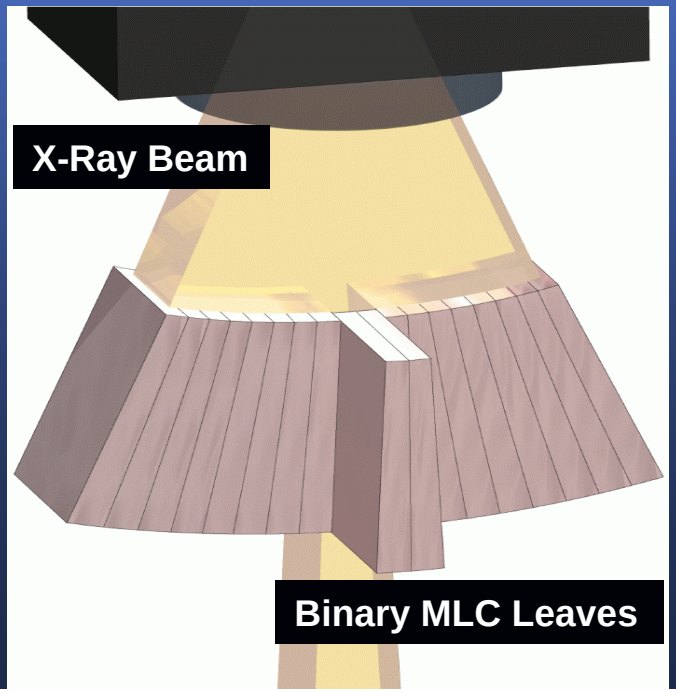


Varian

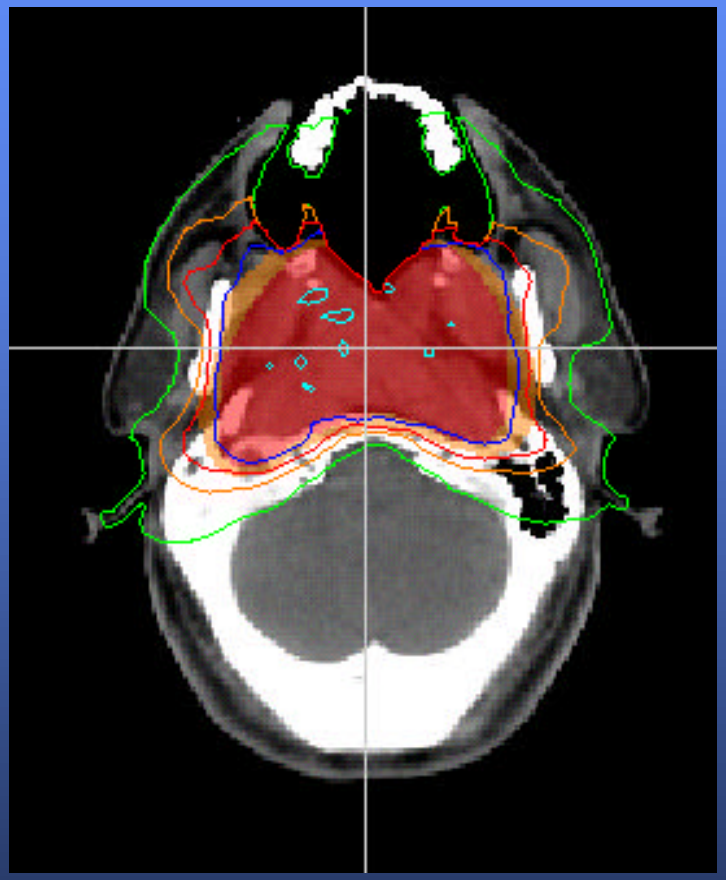
Elekta

Sequential Tomotherapy
The First Form of IMRT

NOMOS Peacock ä System



Binary Multileaf Collimator



Simulated Annealing Optimization

Courtesy: NOMOS Corporation

MIMiC

Multileaf
Intensity
Modulating
Collimator

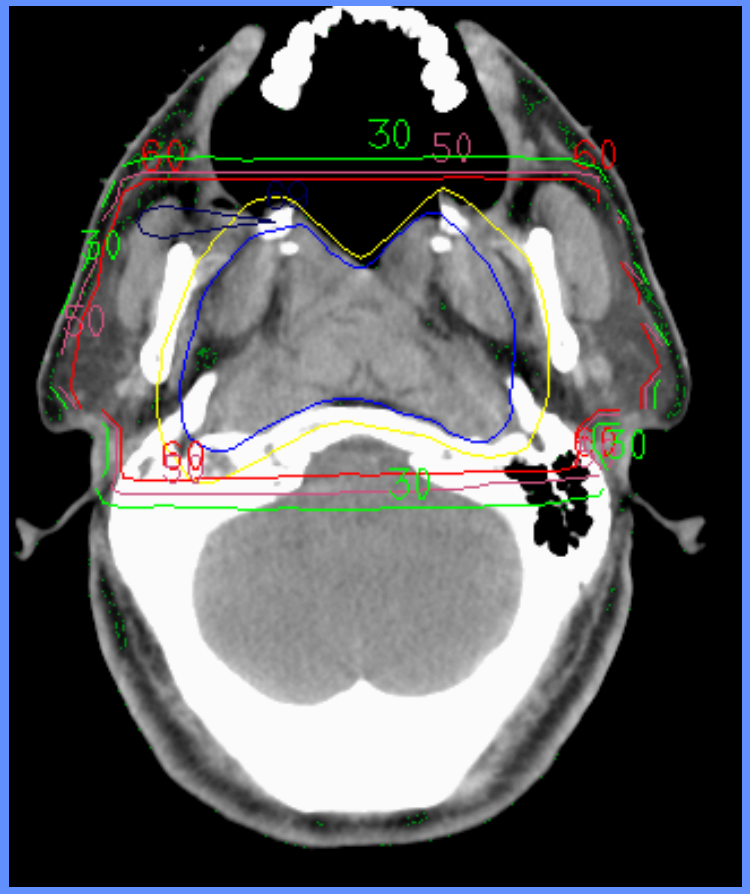
From Bruce Curran, NOMOS

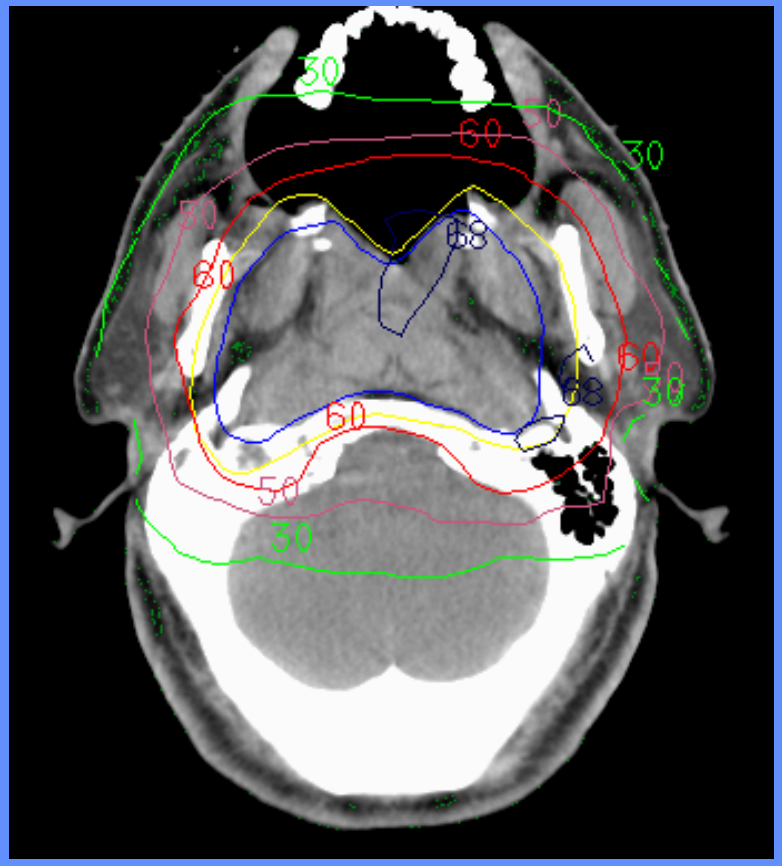
68 Gy

60 Gy

50 Gy

30 Gy

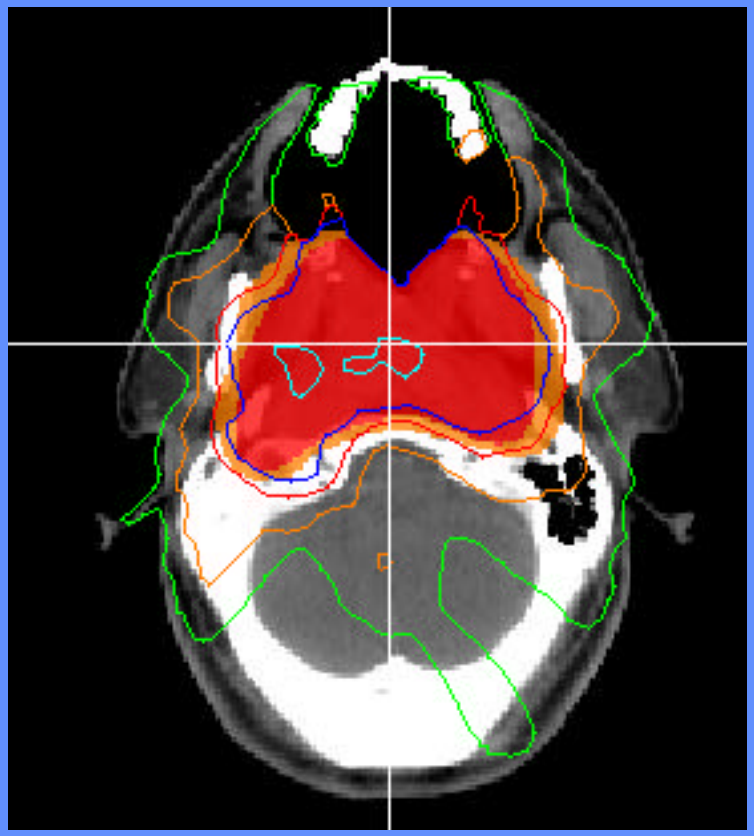


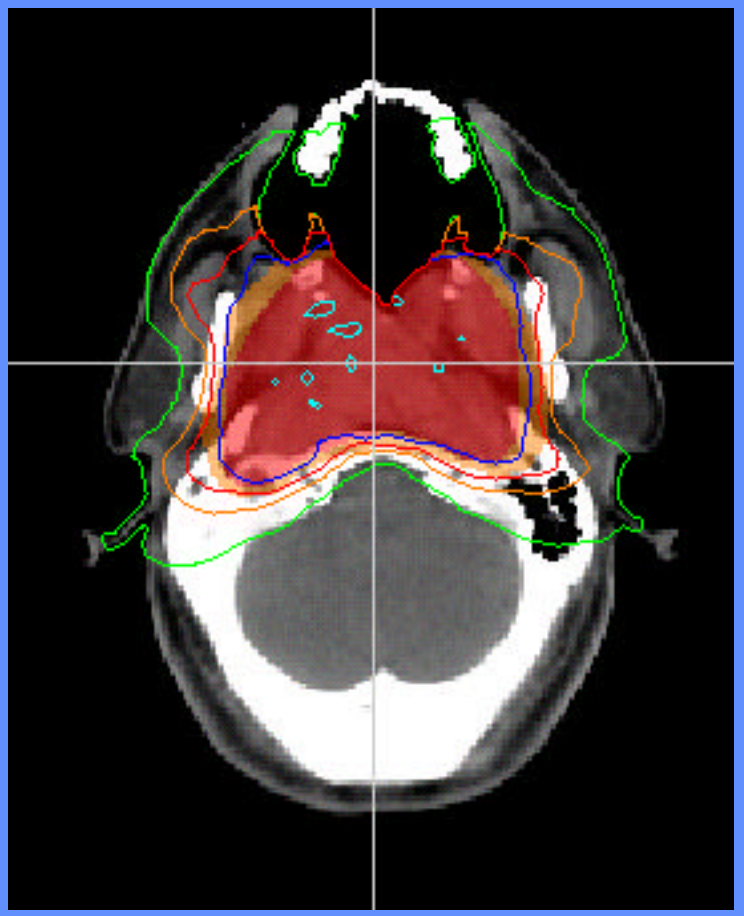


Bi-Lateral

3D-CRT

From Bruce Curran, NOMOS





85Gy

70Gy

60Gy

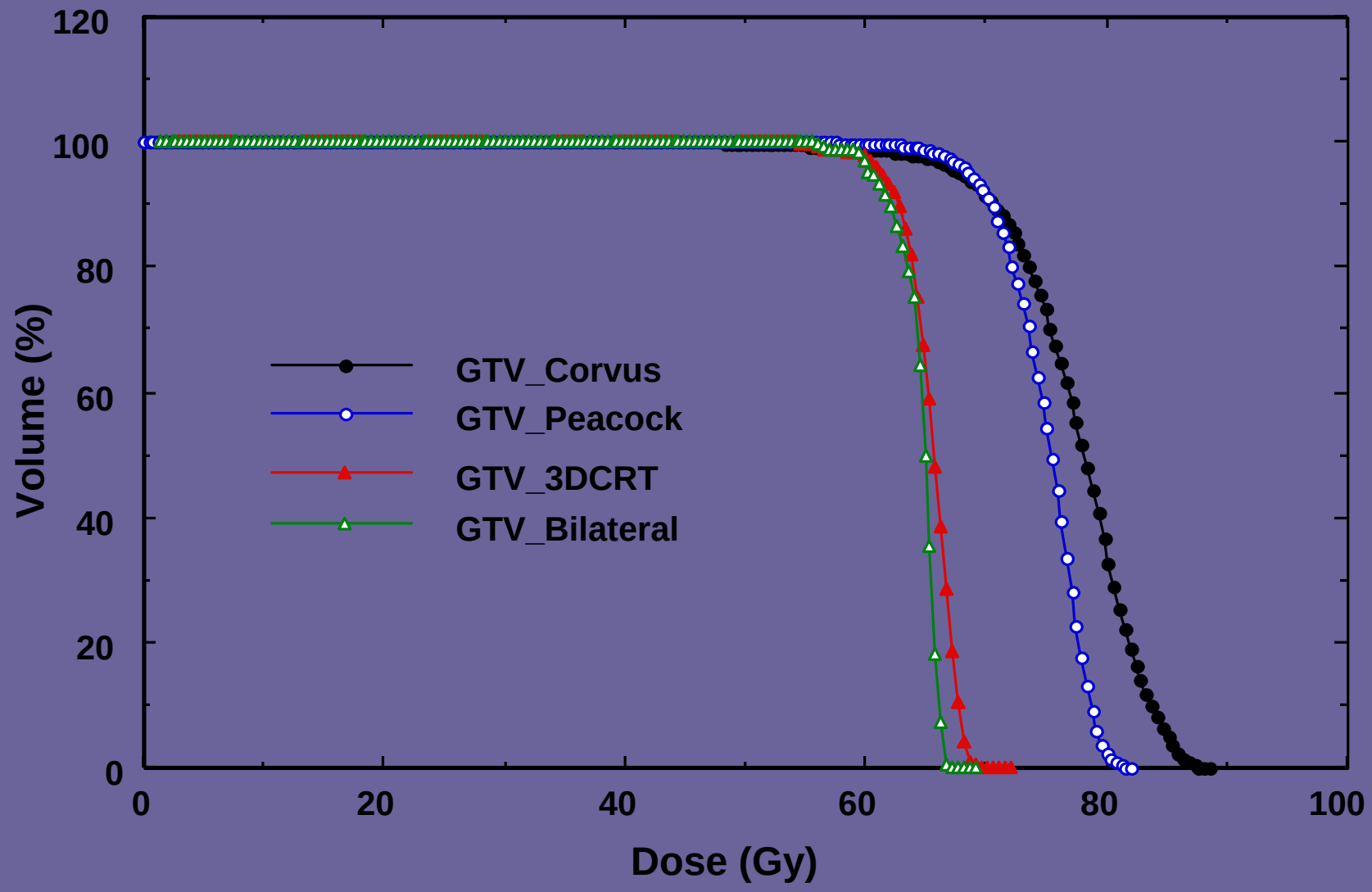
50Gy

30Gy

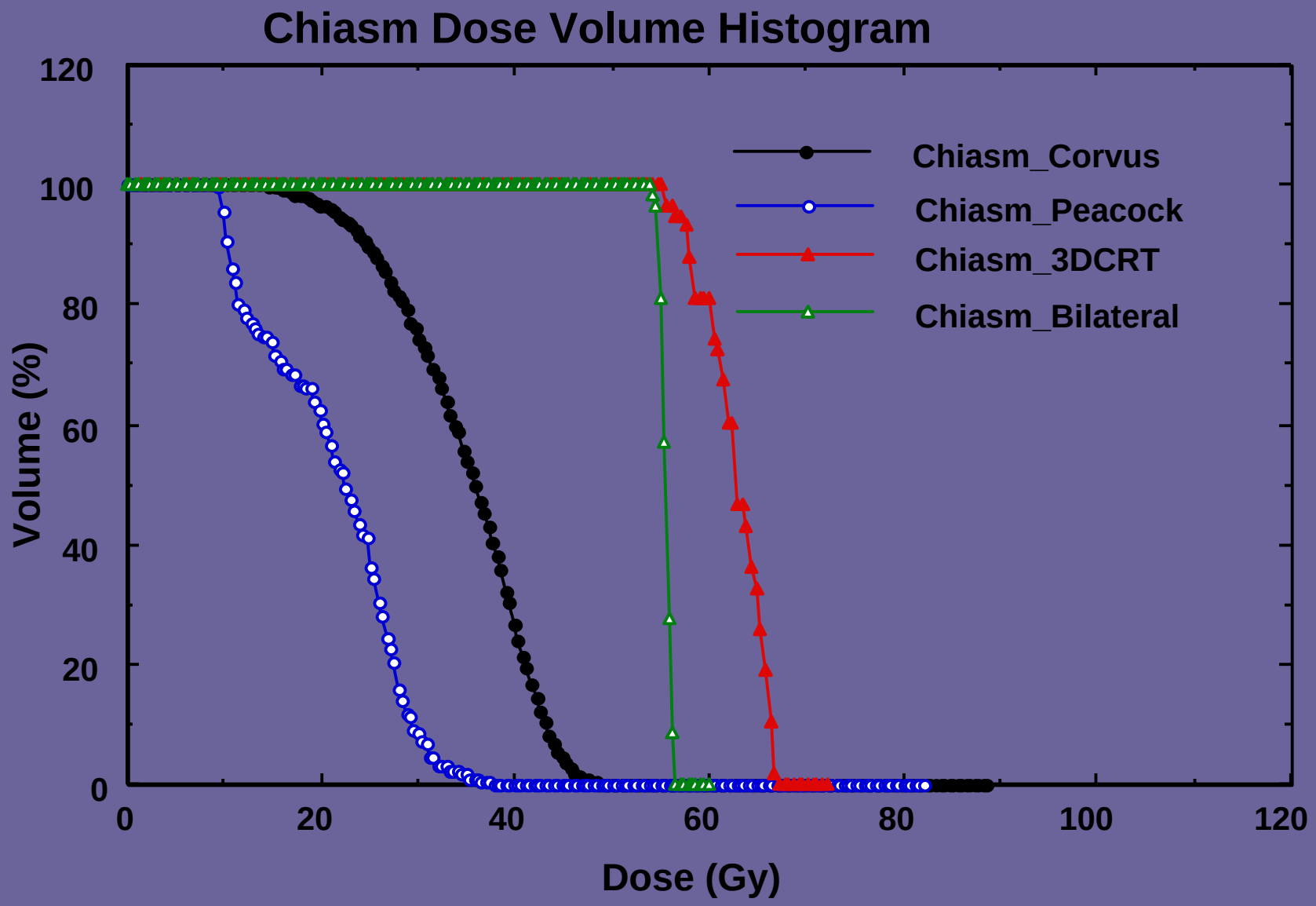
7-Field IMRT (Planned with Corvus)

Sequential Tomotherapy (Nomos Peacock)

From Bruce Curran, NOMOS



From Bruce Curran, NOMOS



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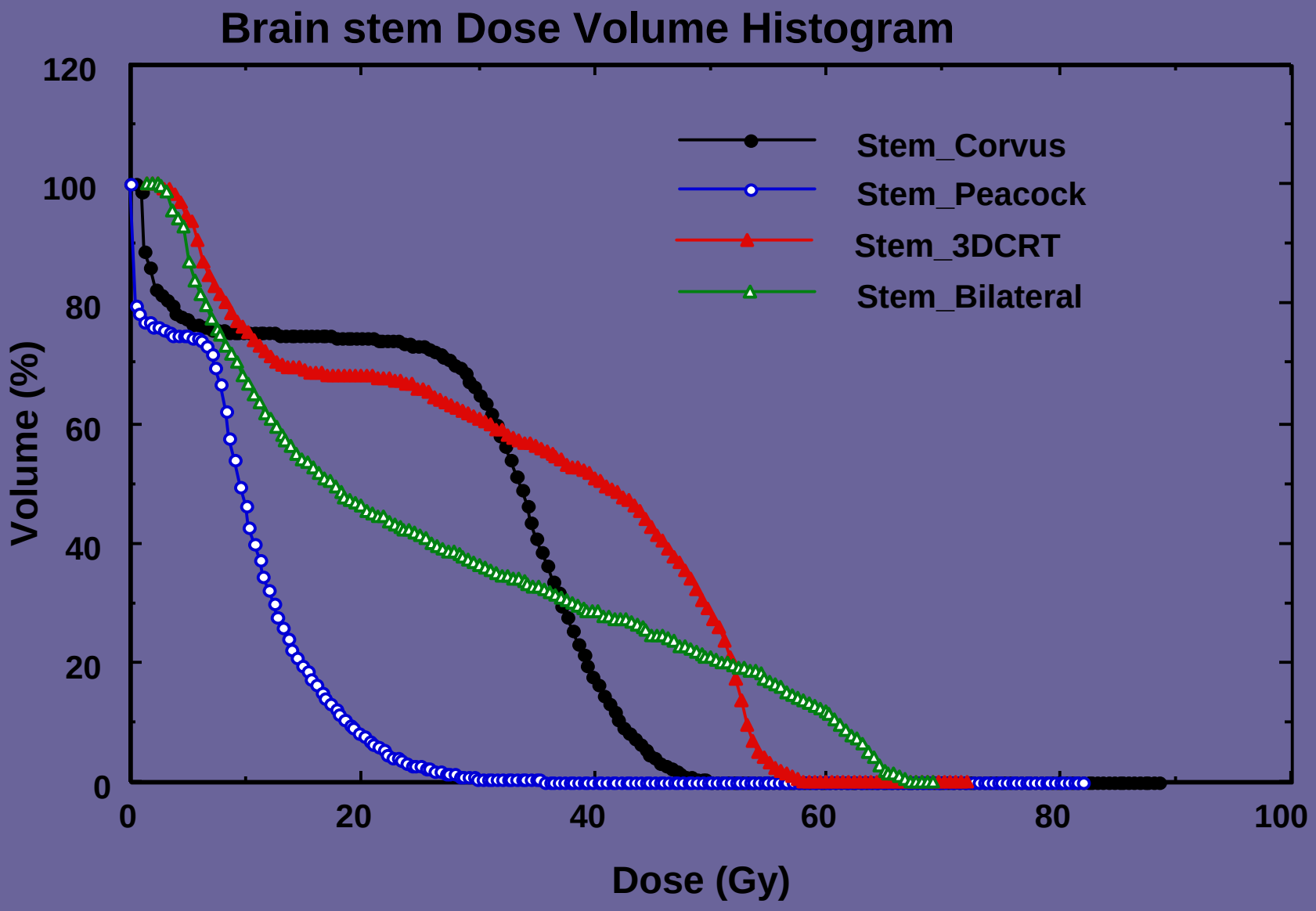
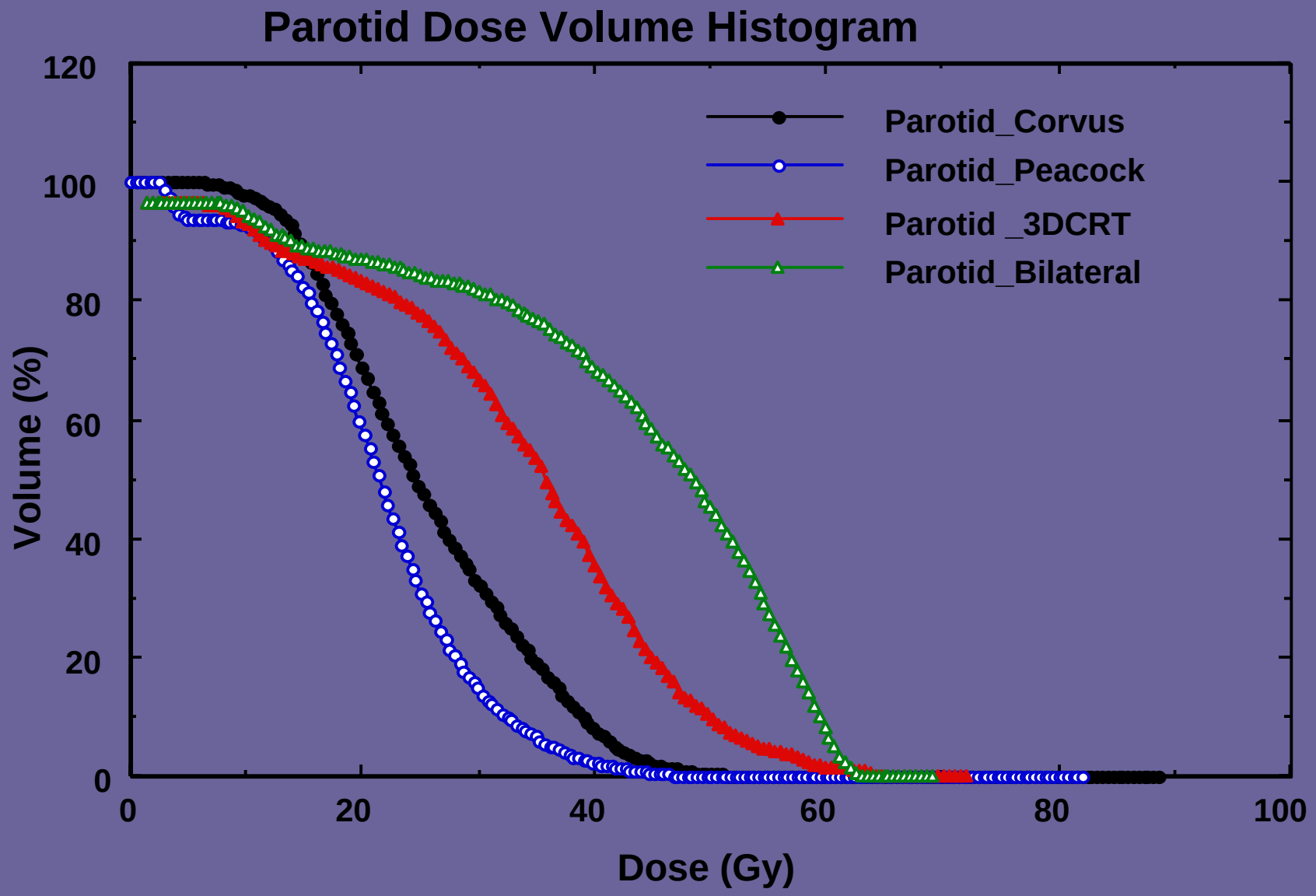
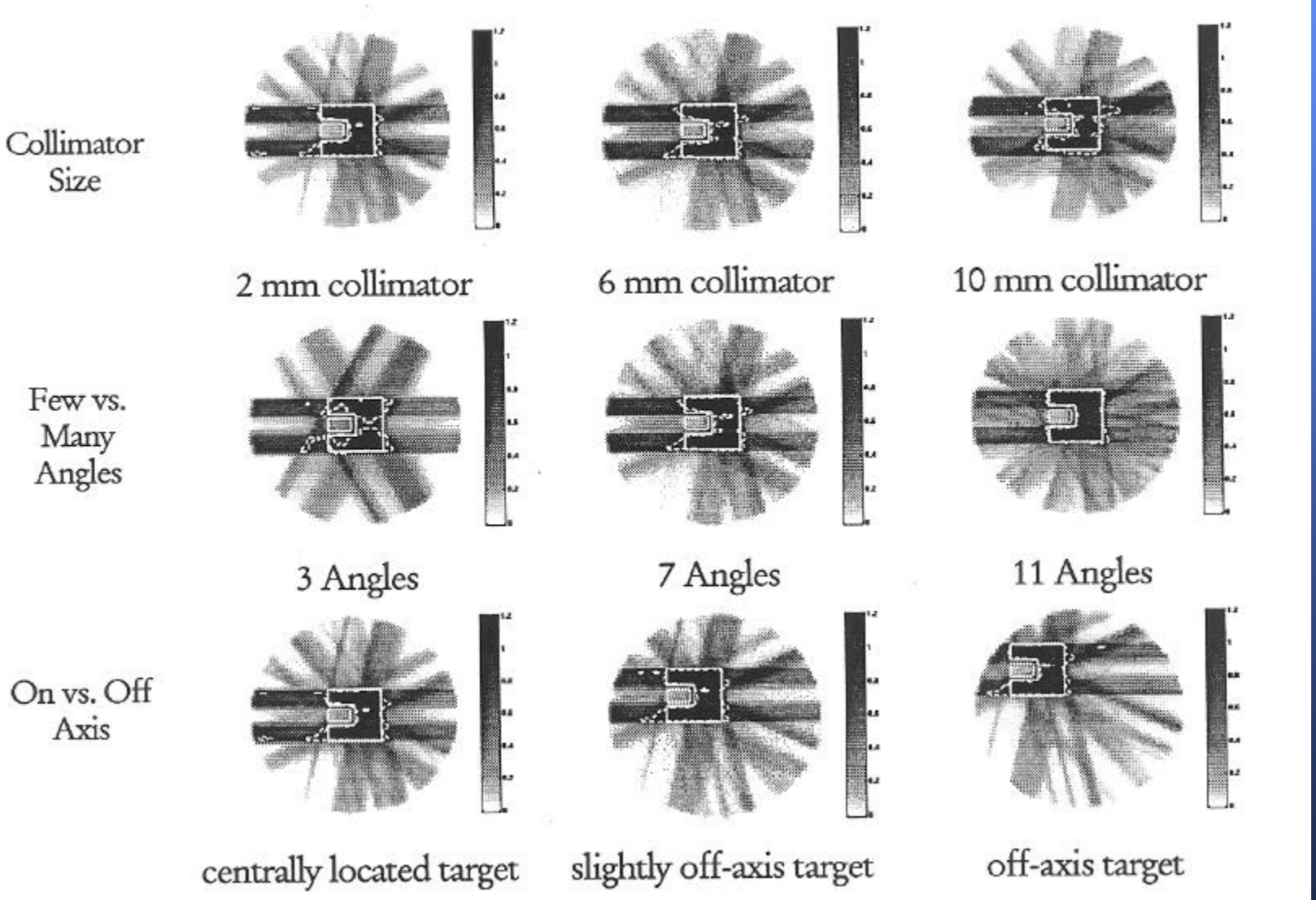


From Bruce Curran, NOMOS



From Bruce Curran, NOMOS

Role of Beam Configuration



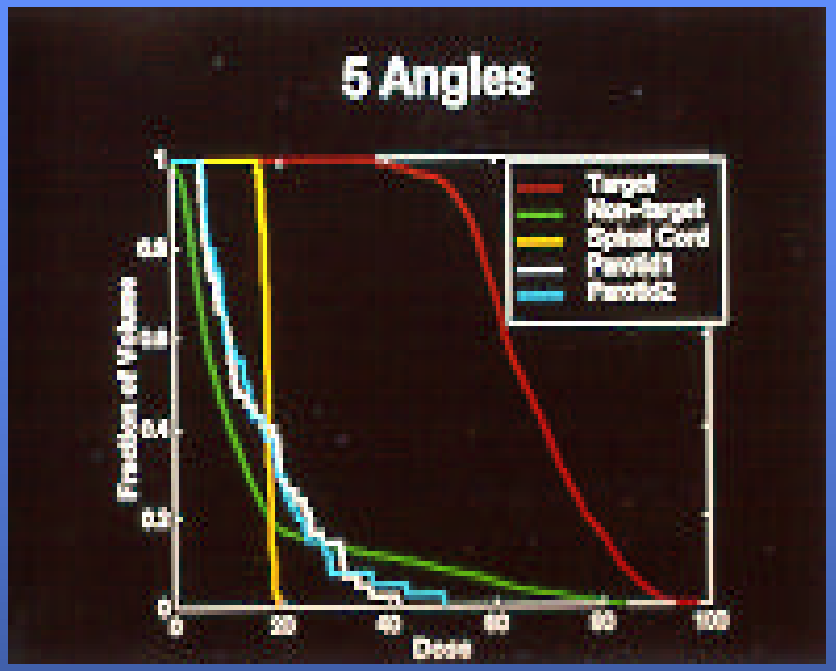
All results for 7 beam directions except where otherwise noted.

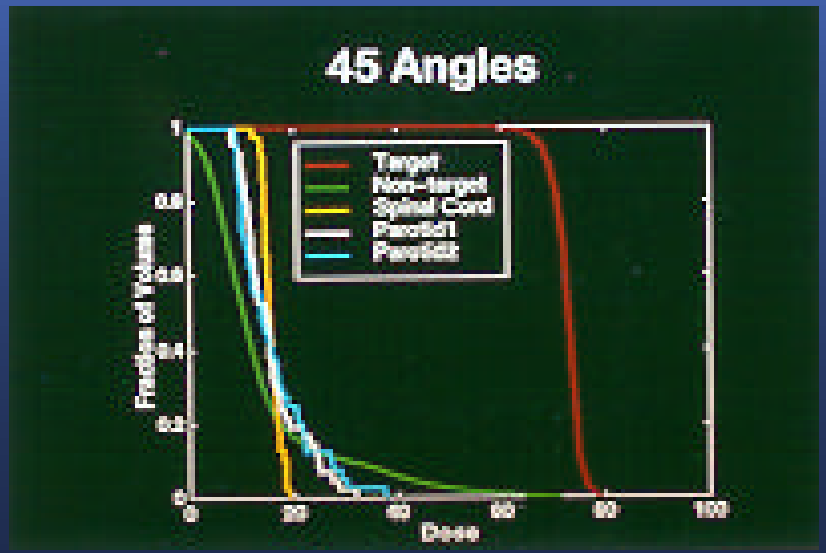
Detailed dependency upo the number of beam directions shown in the nex table.

Dependency Upon Number of Beam Directions

Number of Beam Directions	Objective Function Value	Standard Deviation in the Target Dose	Minimum Dose Covering 90% of the Target (1.0=max)	Mean Dose to the Region at Risk	Total Integral Dose
3	0.665	0.124	0.747	0.488	2733
5	0.318	0.090	0.814	0.215	2564
7	0.242	0.064	0.867	0.206	2597
9	0.222	0.064	0.855	0.192	2599
11	0.202	0.058	0.879	0.186	2570
15	0.187	0.053	0.908	0.180	2542
21	0.176	0.049	0.912	0.171	2545
33	0.151	0.038	0.933	0.155	2544

Nasopharyngeal Example



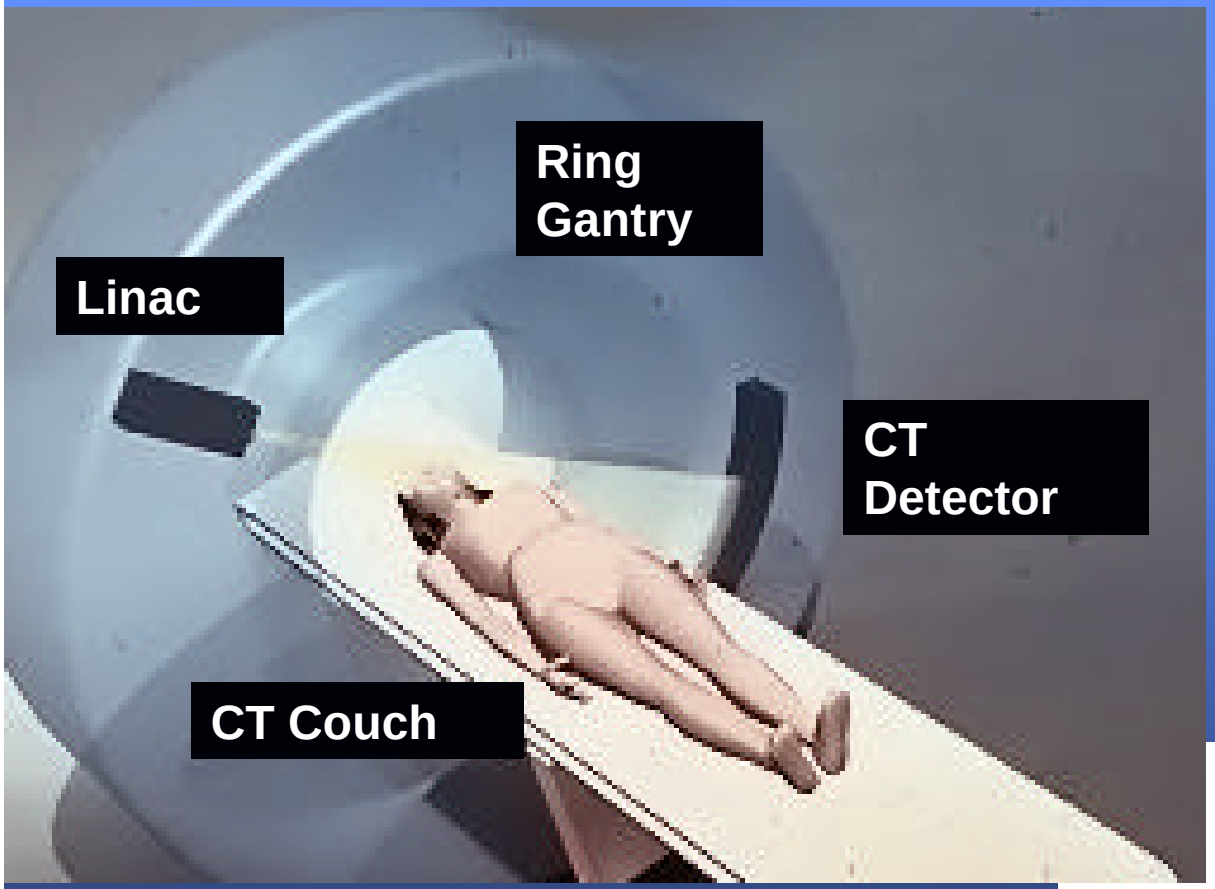


In this case the primary goal was to avoid the parotid and spinal cord. With the same amount of avoidance, the 45 angle delivery (tomotherapy) provided a more homogeneous delivery.

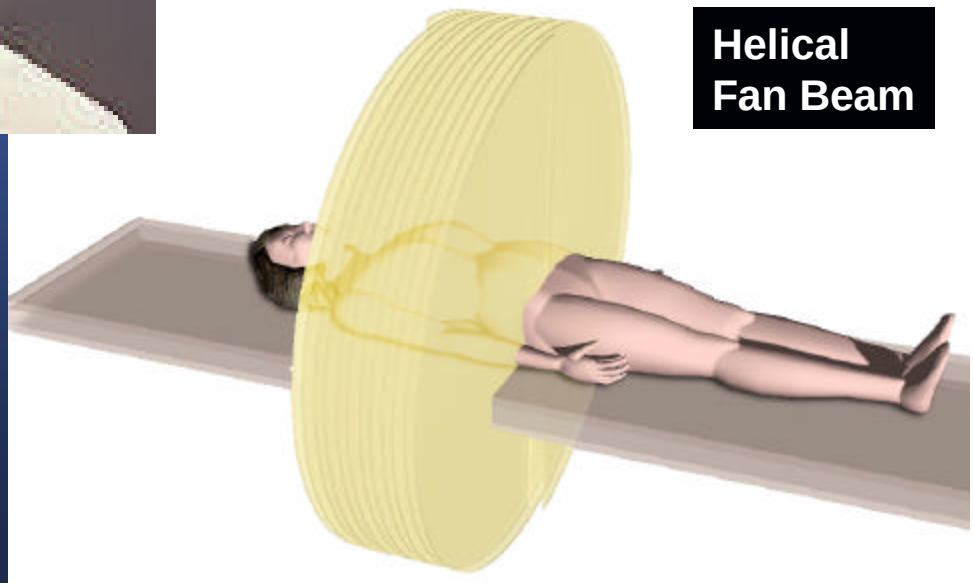
Re-Engineering Radiotherapy

- Equipment and processes re-engineered for IMRT
- Integration of planning, delivery and verification
- Better leaf resolution
- Simple MLC’s
- More beam directions
- Single energy photon beam
- Better primary shielding
- Tomographic verification
- Helical tomotherapy was the result

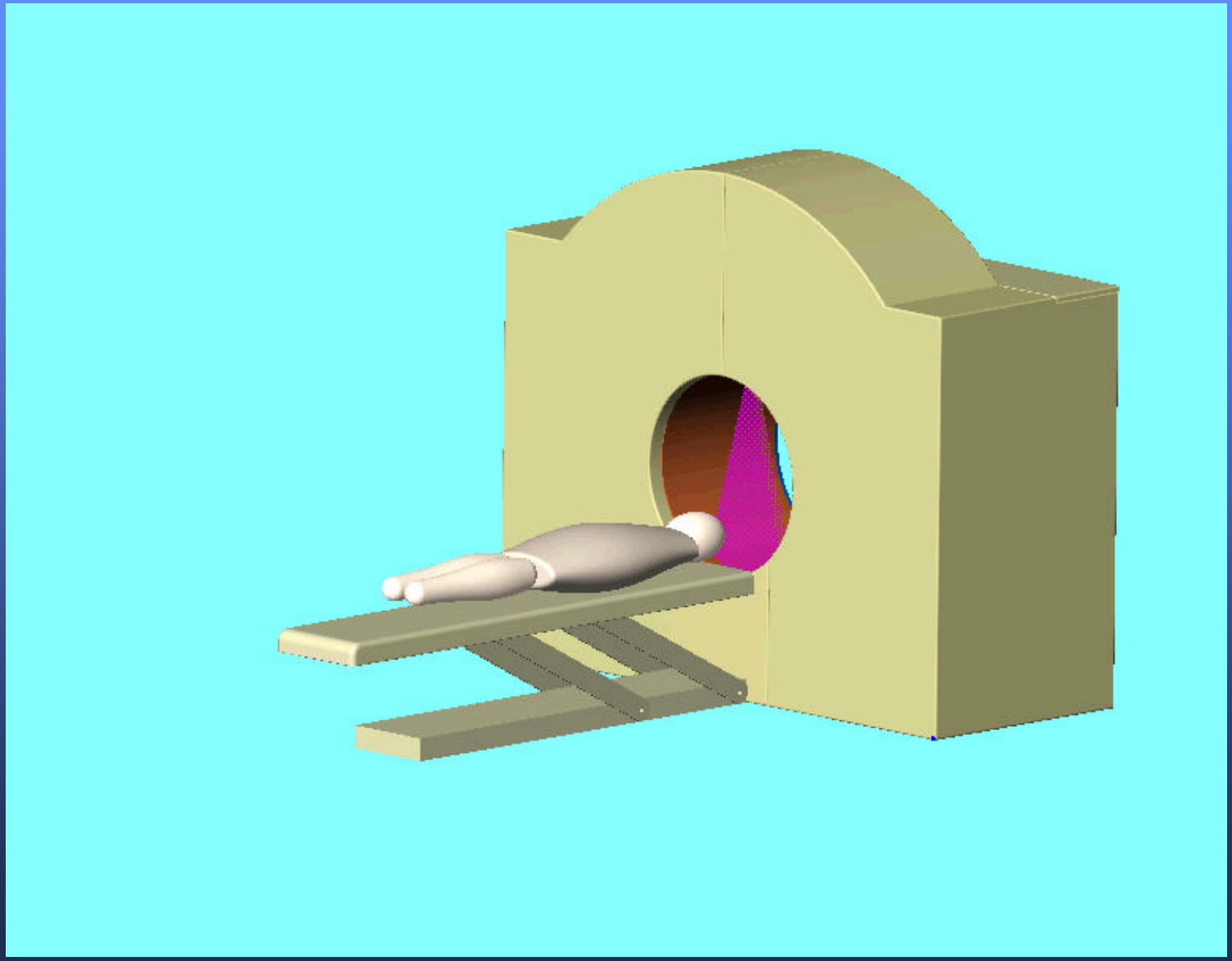
Helical (Spiral) Tomotherapy



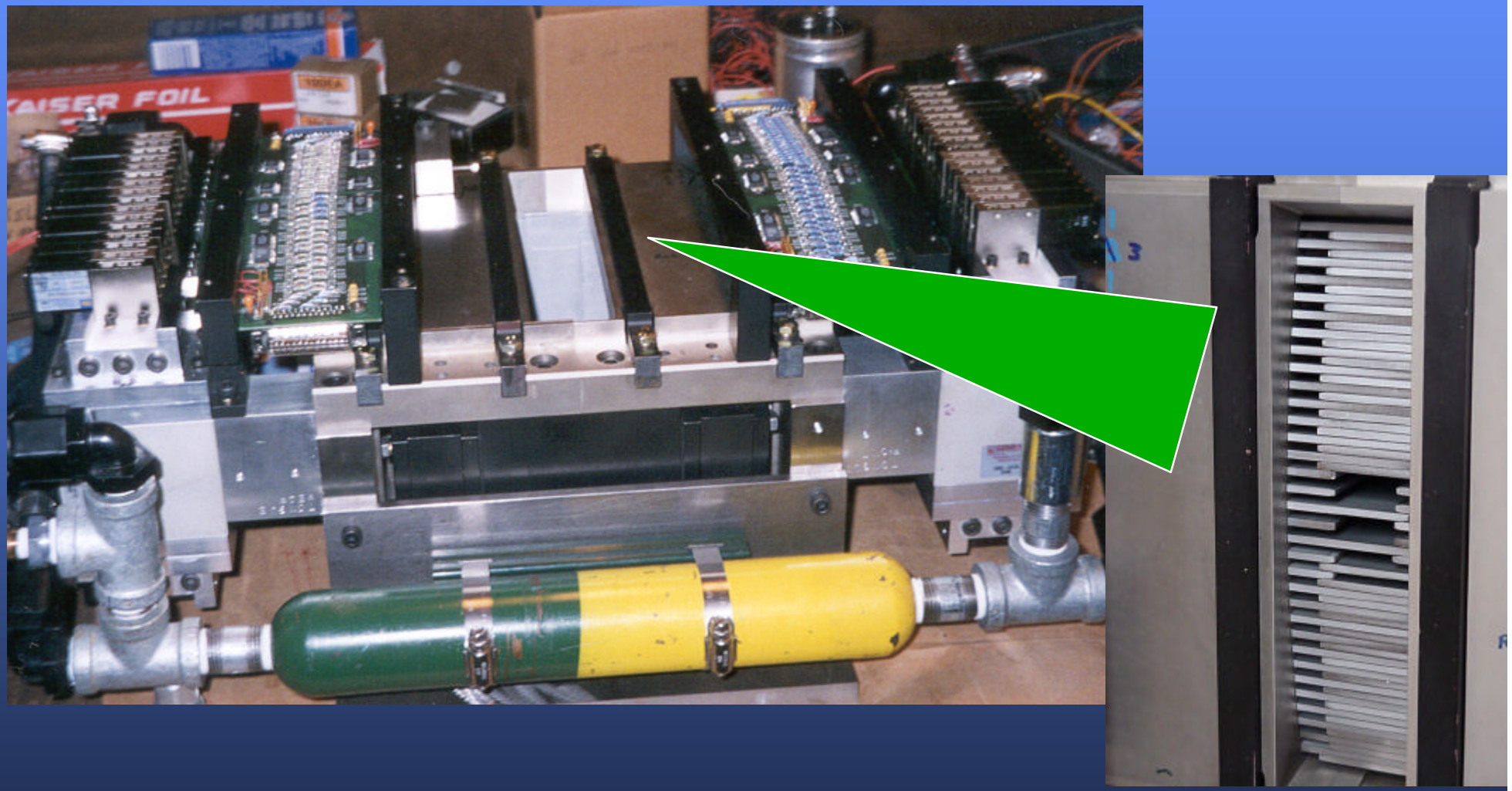
Helical Scanning



Animation of Helical Delivery

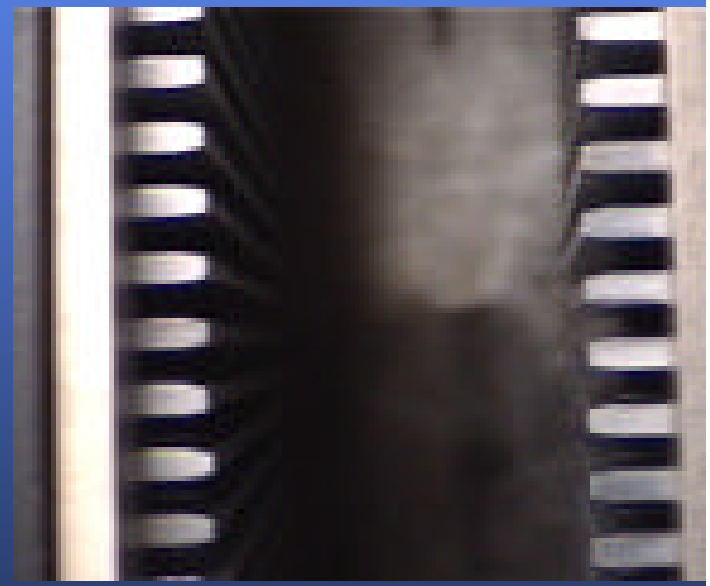


64 Leaf Binary MLC



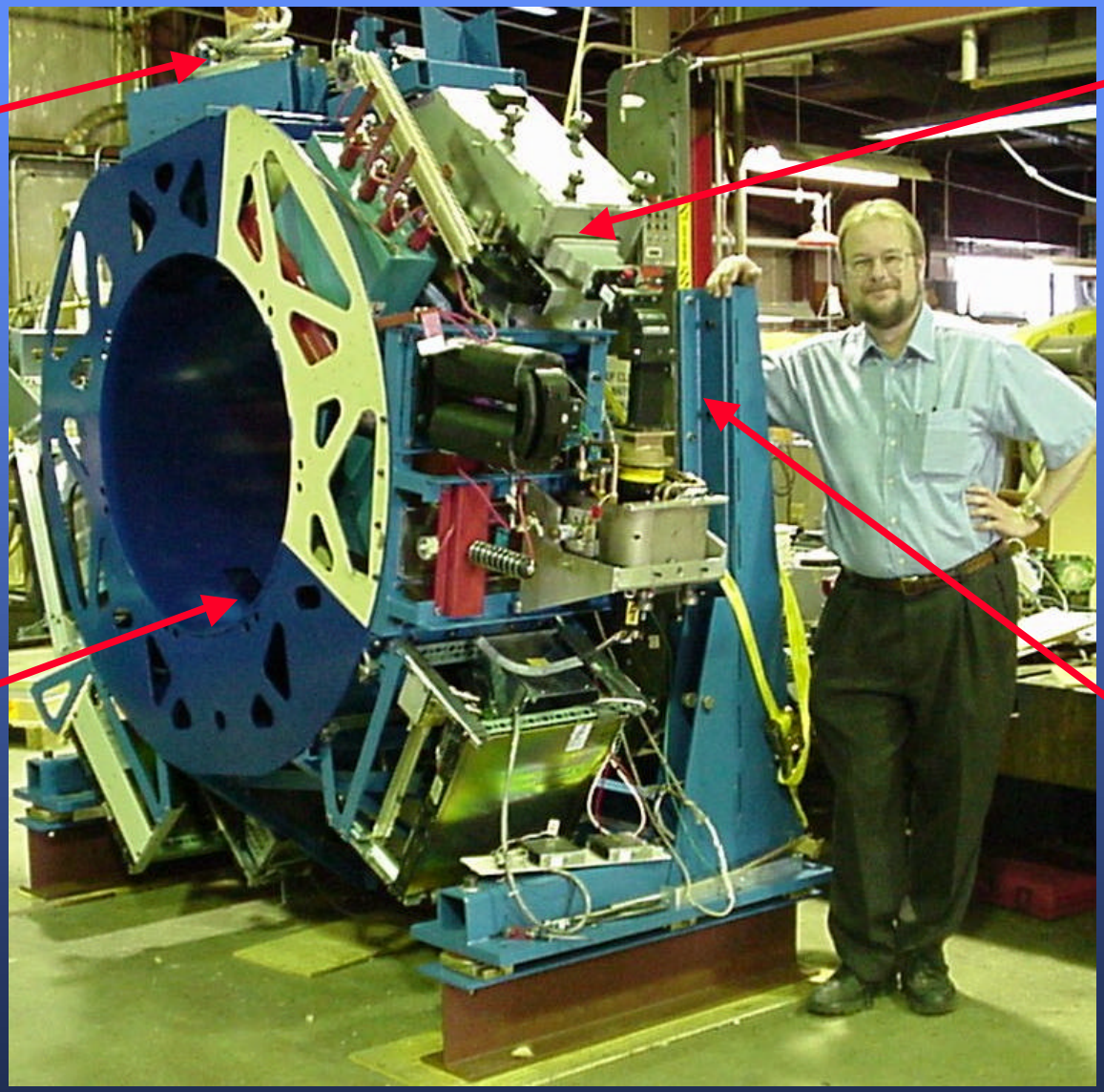
Close-Up

Movie Clips of the MLC Being Tested



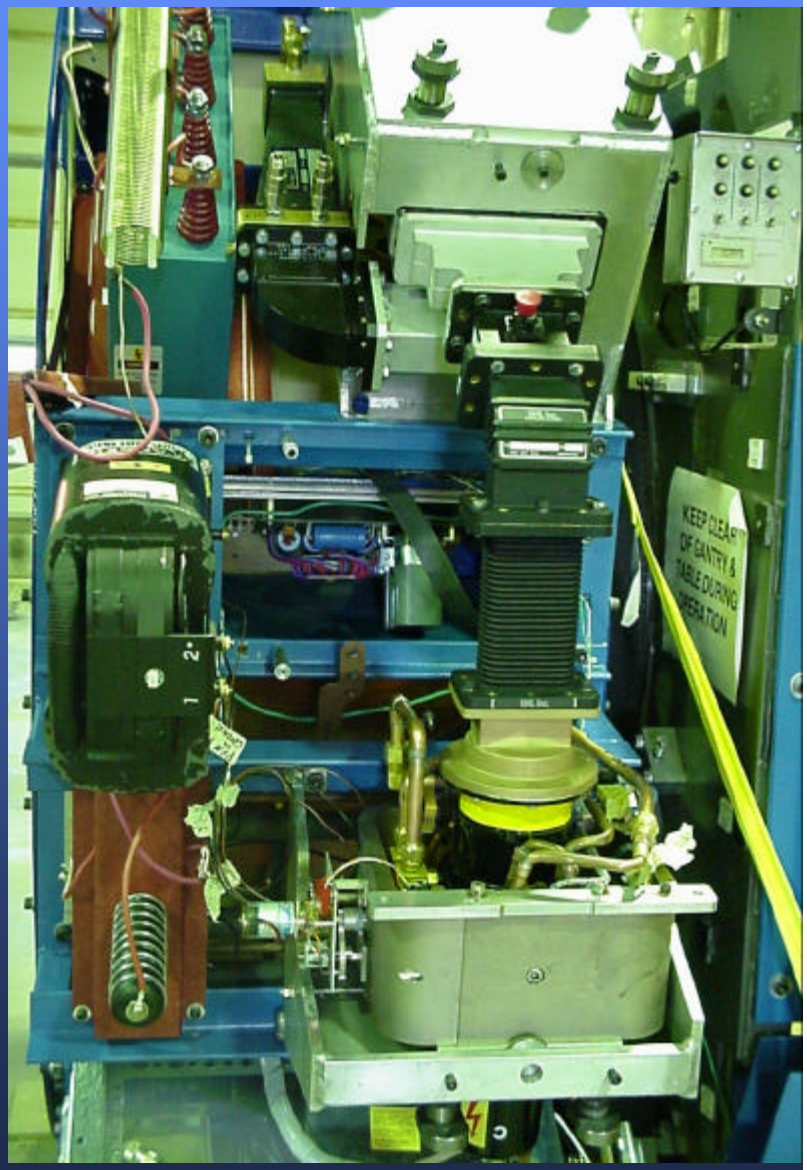
Close-Up

UW Clinical Helical Tomotherapy Unit



May 2000 at UW Physical Sciences Laboratory, Stoughton WI

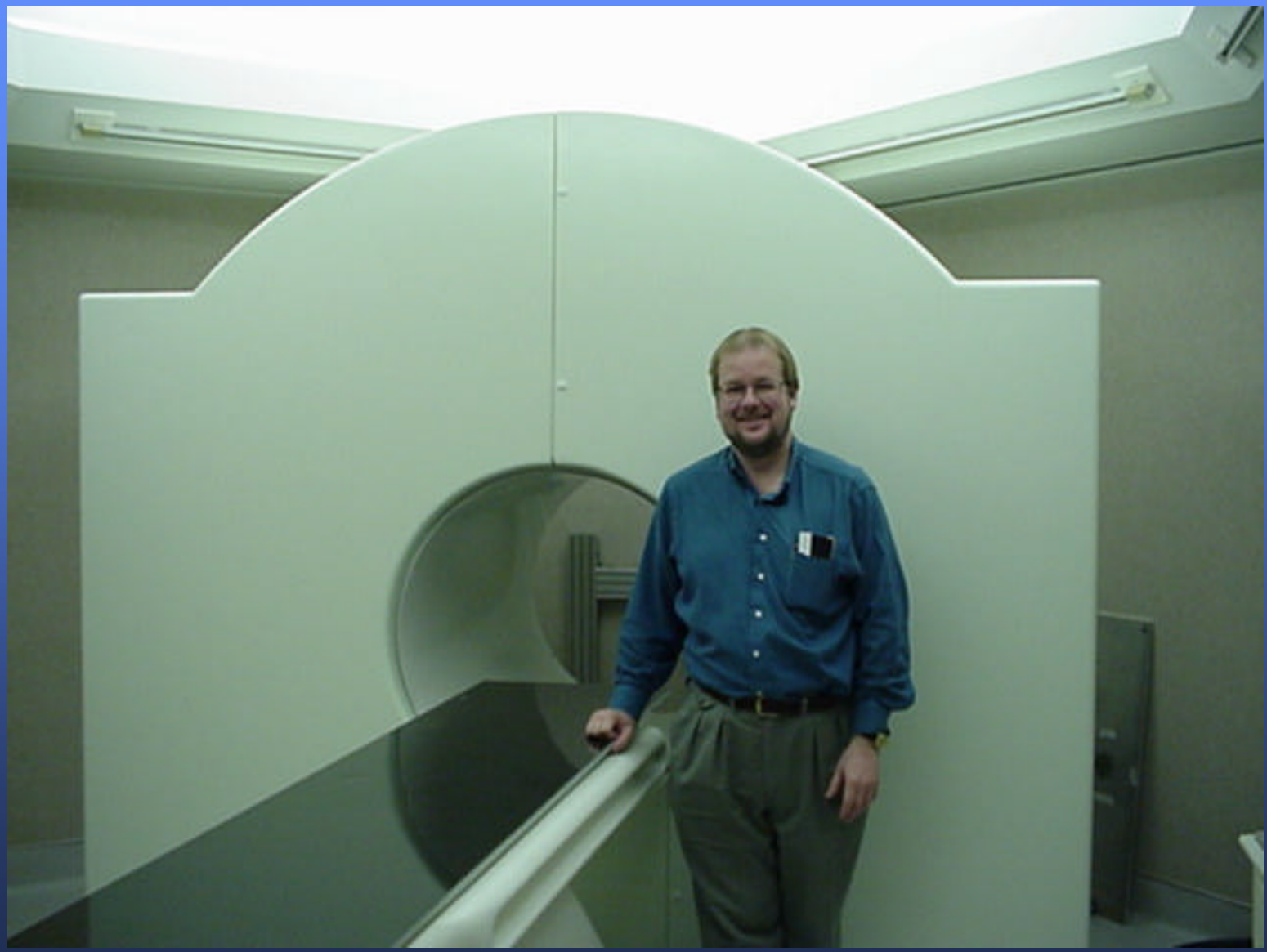
Siemens 6 MV Linac System



Linac and Gun Control

RF System

Clinical Installation Finished



January 16, 2001 at UW Radiotherapy Clinic

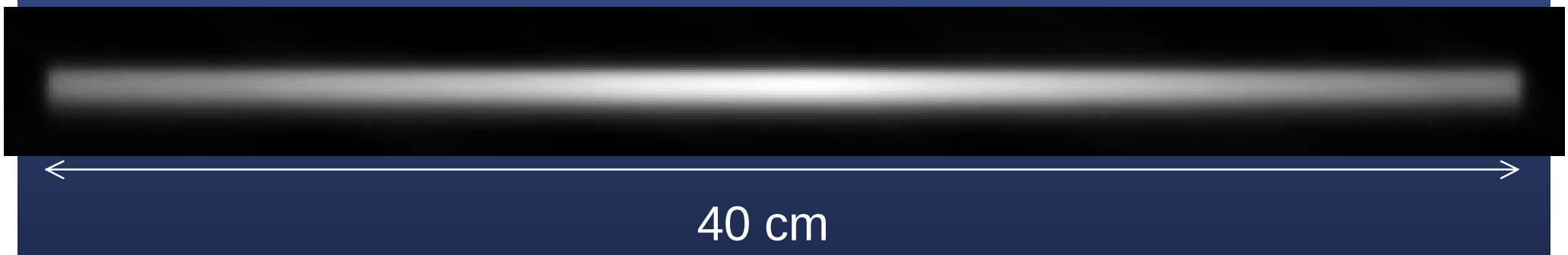
Major Specifications

- 6 MV Siemens linac
- Up to 8 Gy/min @ axis
- 85 cm diameter gantry bore
- 64 leaves with 6.25 mm resolution @ axis
- 4 cm x 40 cm maximum field @ axis
- Slice field width from 5 mm to 40 mm @ axis
- Minimum beamlet size 5 mm x 6.25 mm @ axis
- Xenon CT detectors with per pulse acquisition
- 0.25 mm precision CT couch
- Leaves 10 cm thick, 95% tungsten alloy
- Primary collimator 22 cm thick 95% tungsten alloy

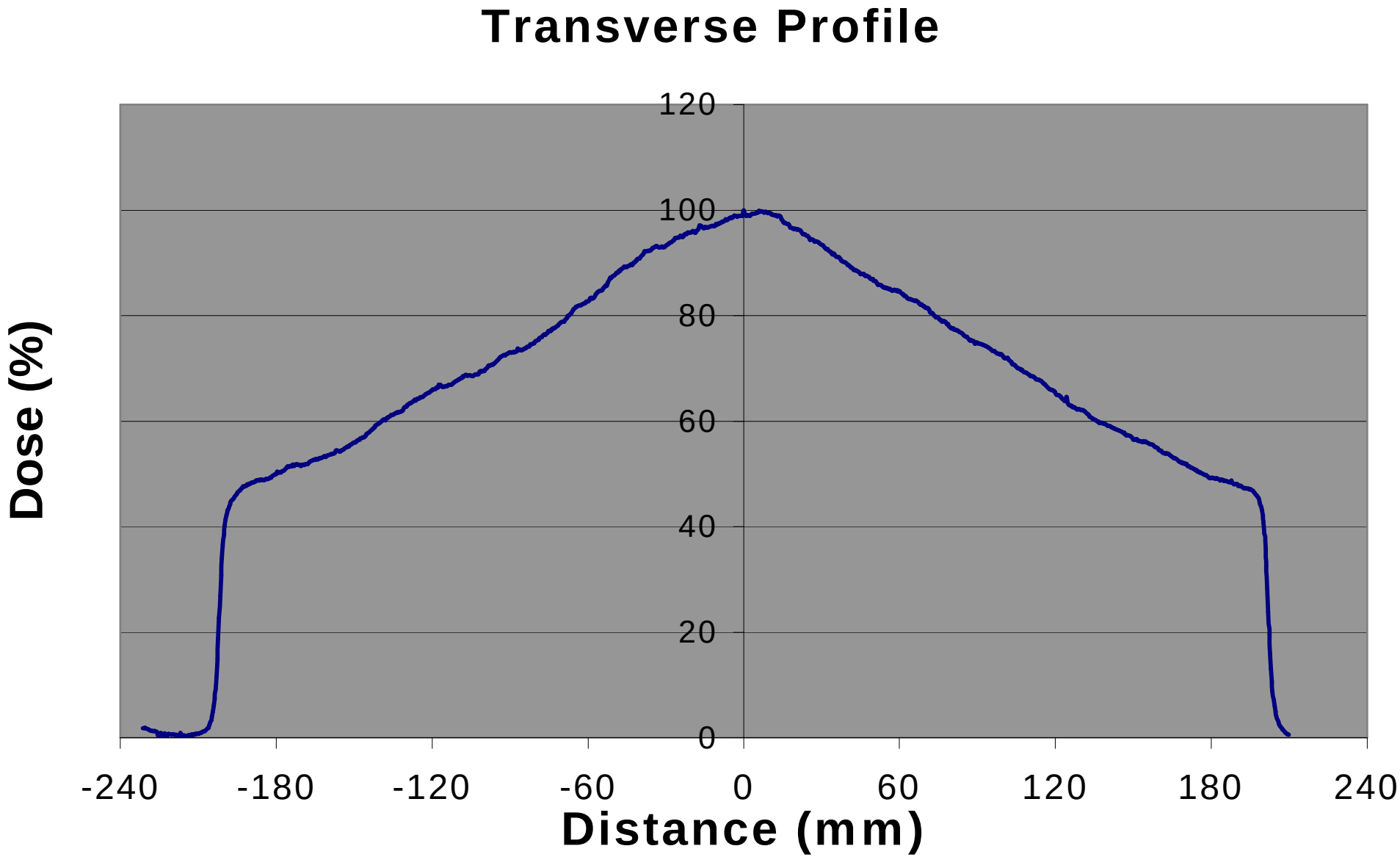
Fan Beam Characteristics

- The fan field width along the longitudinal direction is continuous from 5 mm to 50 mm.
- There is no field flattening filter in the beam and so the beam has a higher intensity along the center as compared to either end.
- The beam without filtration is like the output from a CT “Bowtie Filter”.

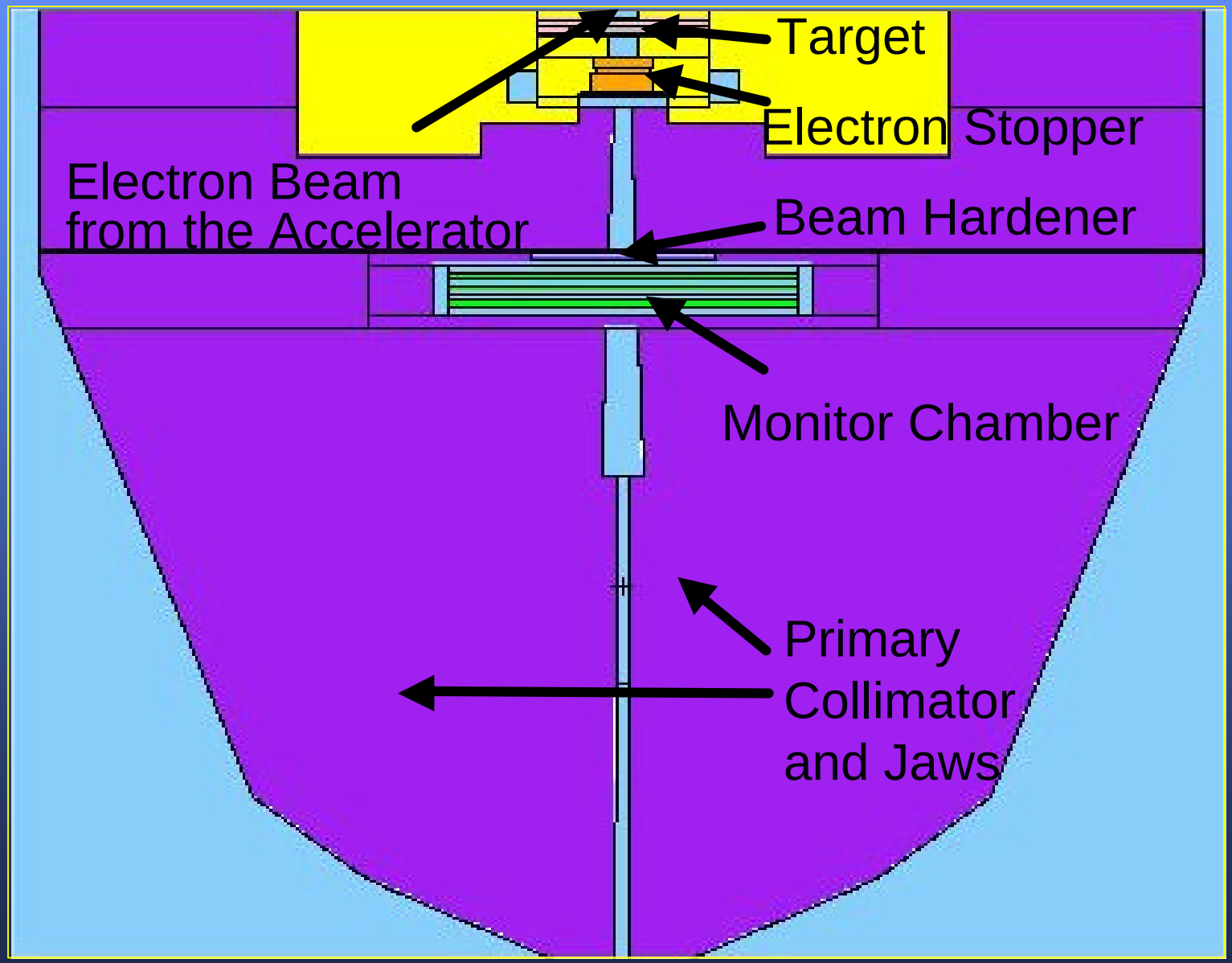
Image Digitized from Kodak XV Film



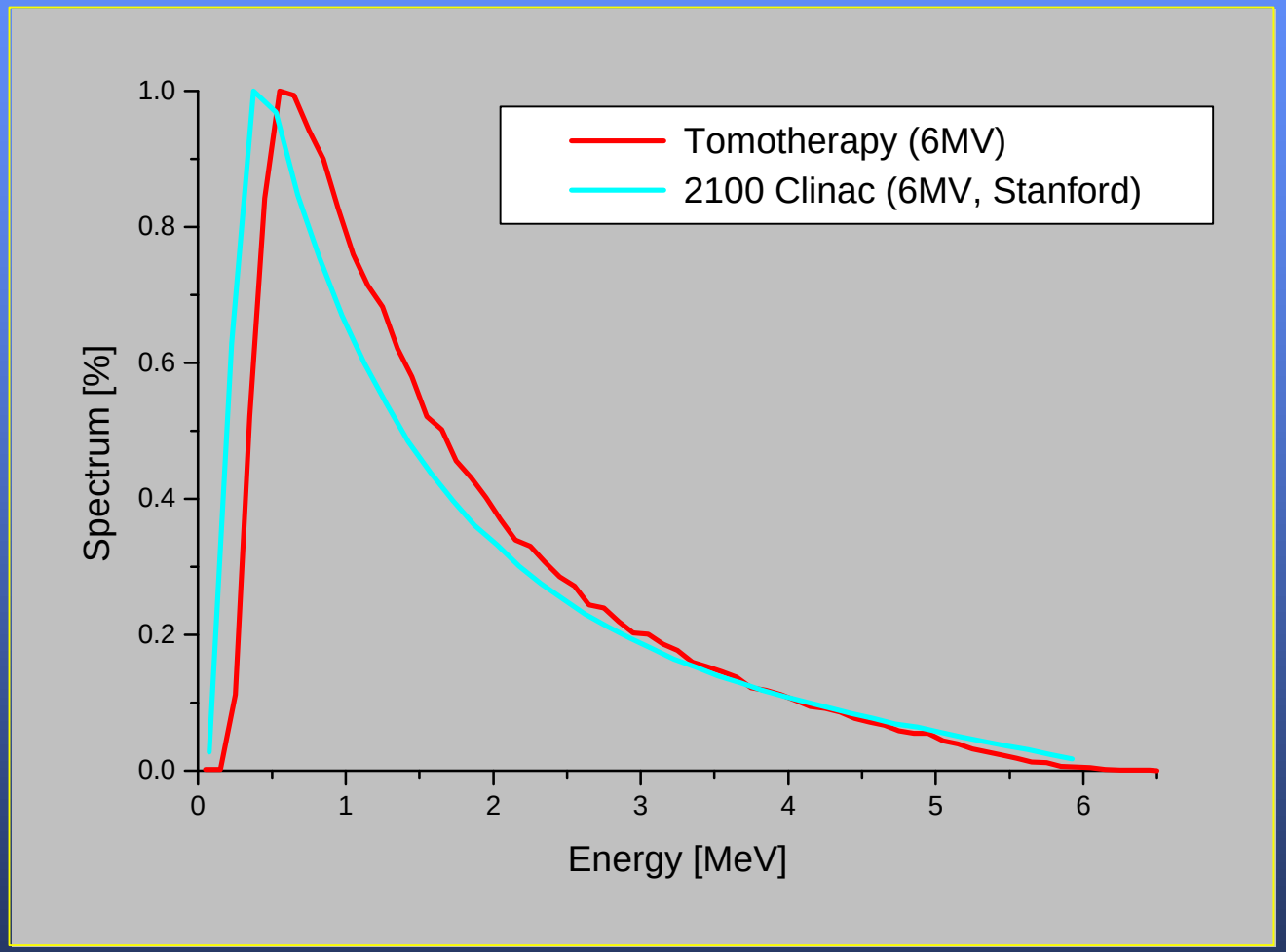
Profile Along Length of a 1 cm Wide Fan Beam



Monte Carlo Model of the Treatment Head



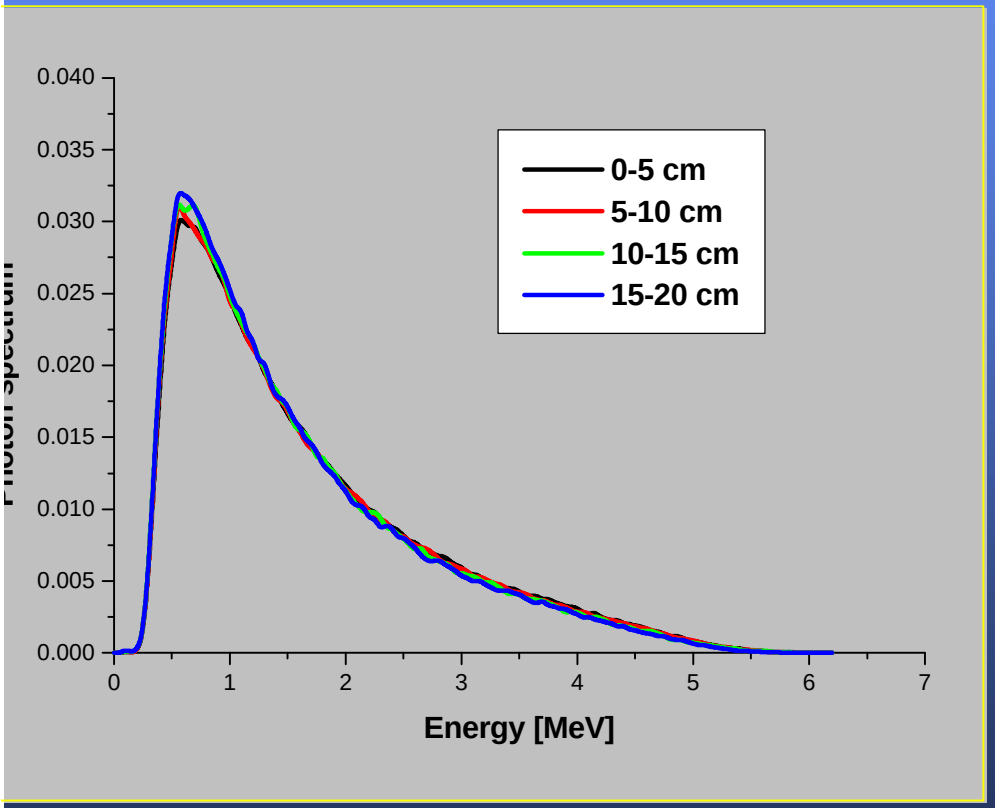
Photon Spectrum

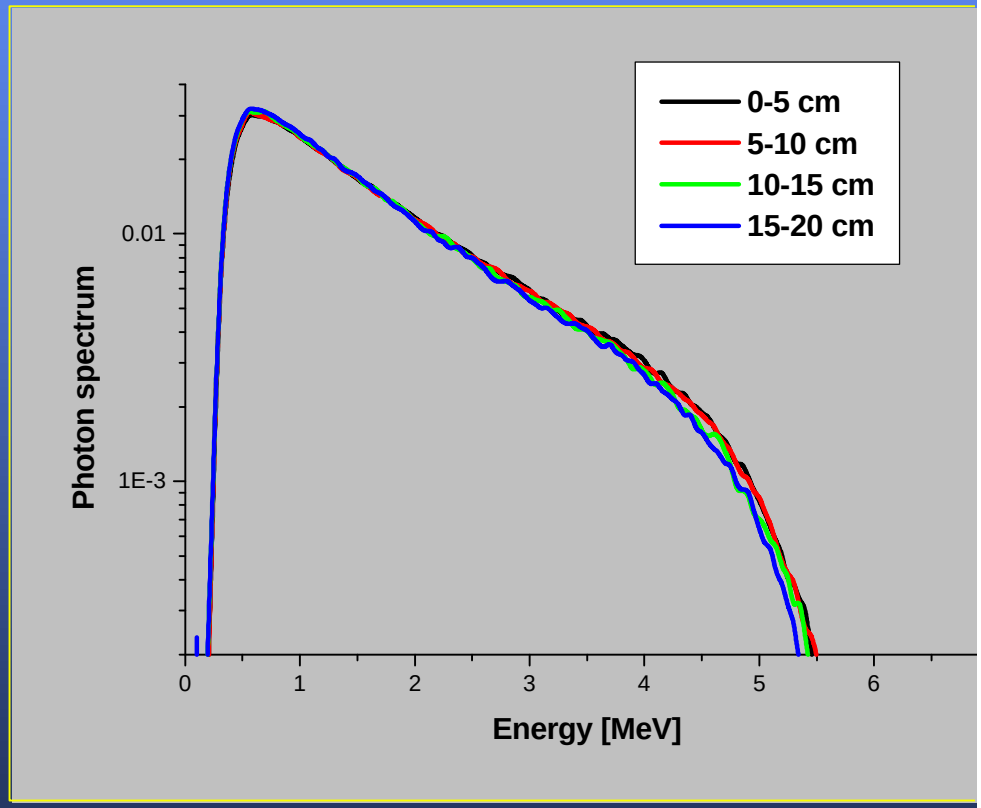


Clinac 2100 Monte Carlo data courtesy o Dr. Charlie Ma

For the same incident energy, tomotherapy has a harder spectrum due to its beam hardener and absence of a field flattening filter.

Off-Axis Energy Dependence



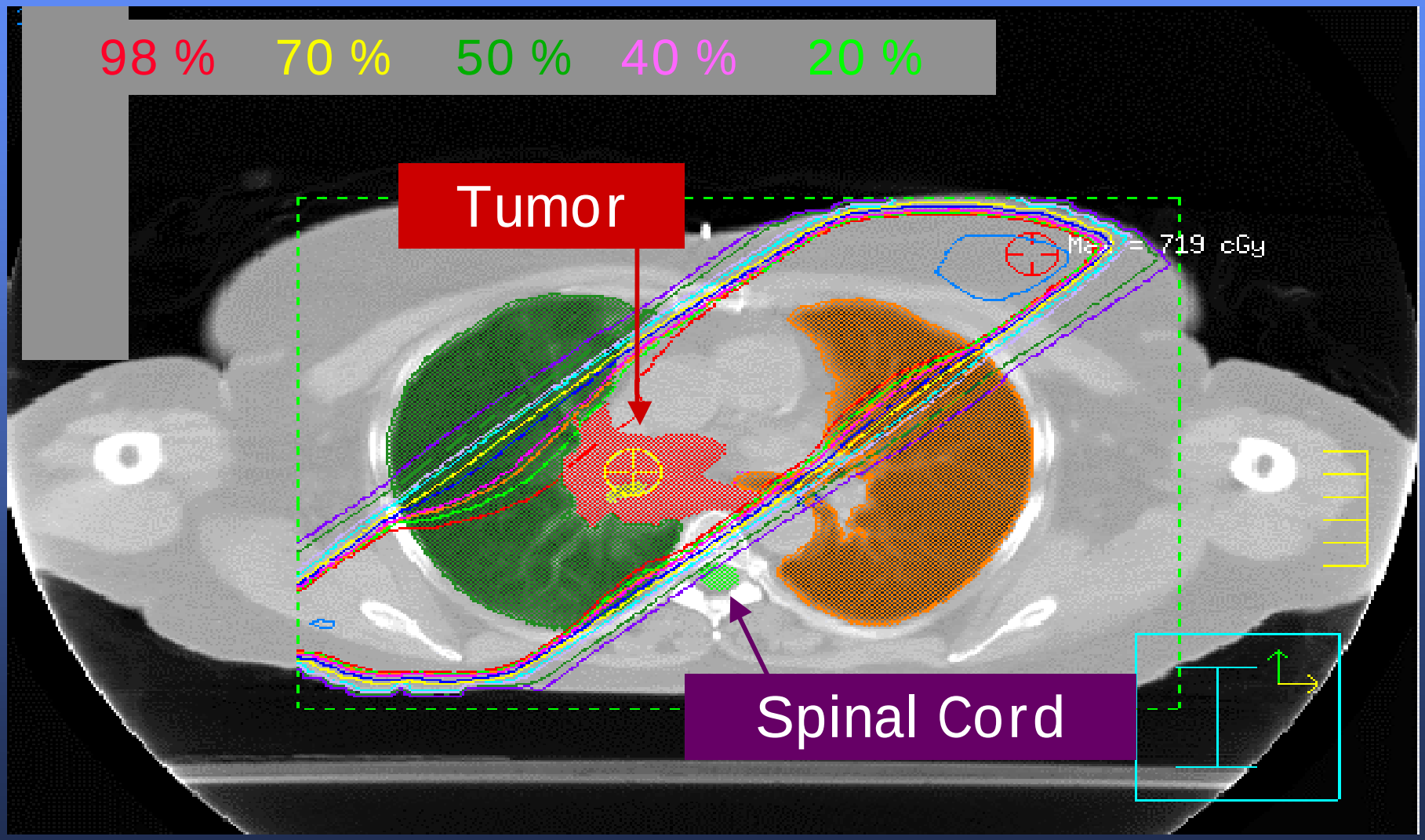


Tomotherapy has no off axis hardening because of no flattening filte

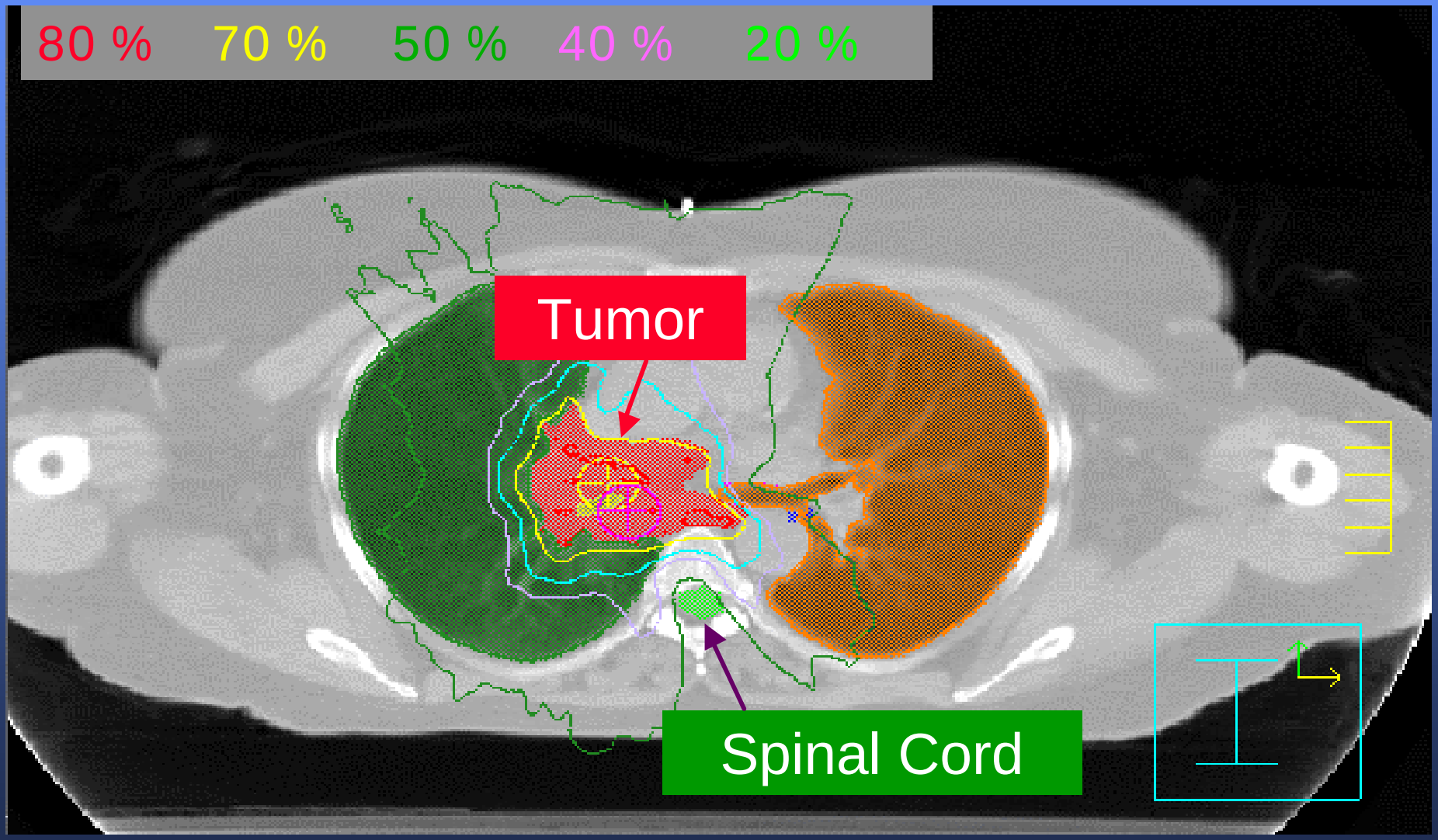
Simplicity of Tomotherapy

Tomotherapy	Conventional RT
Designed for Image-Guided IMRT	Designed for Conventional RT Processes
Single Photon Energy	Dual Mode Multiple Energy
Simple MLC	Complex MLC
No Collimator Rotation	Collimator Rotation
No Couch Rotation	One or Two Axes of Couch Rotation
Simple CT Detector	2D Electronic Portal Imager
System Integration	Multi-Component Integration

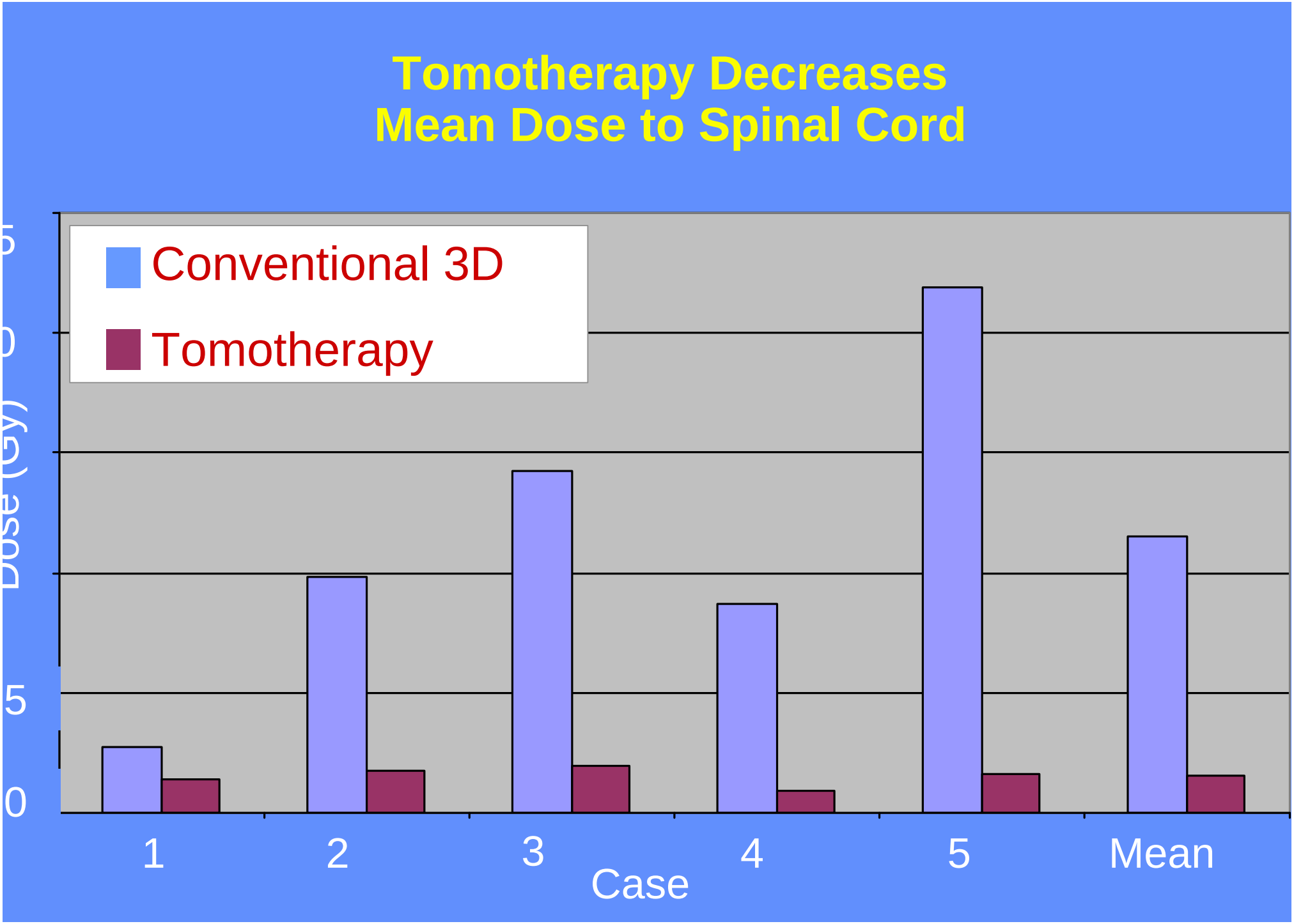
Conventional Plan to Treat Lung Cancer



Tomotherapy Plan to Treat Lung Cancer

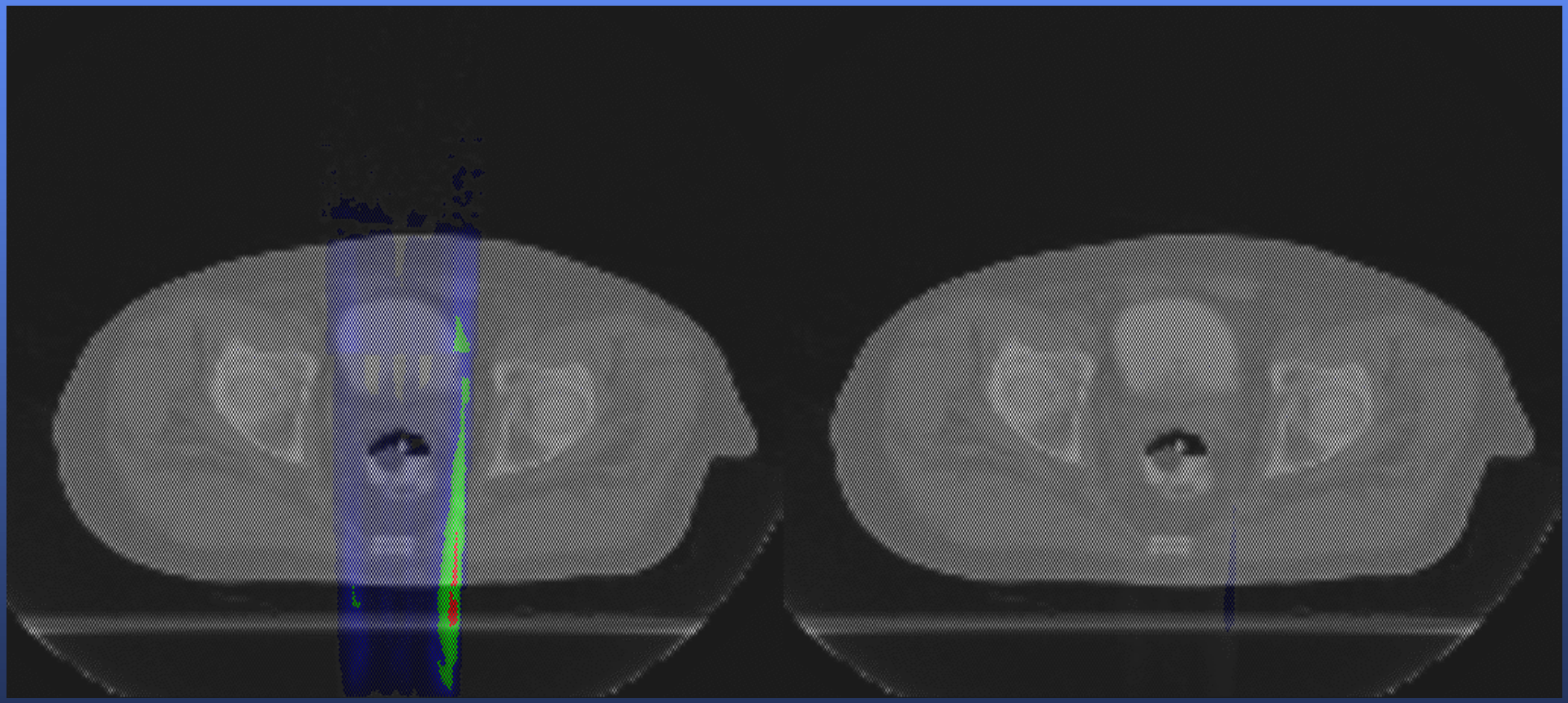


Tomotherapy Decreases Mean Dose to Spinal Cord



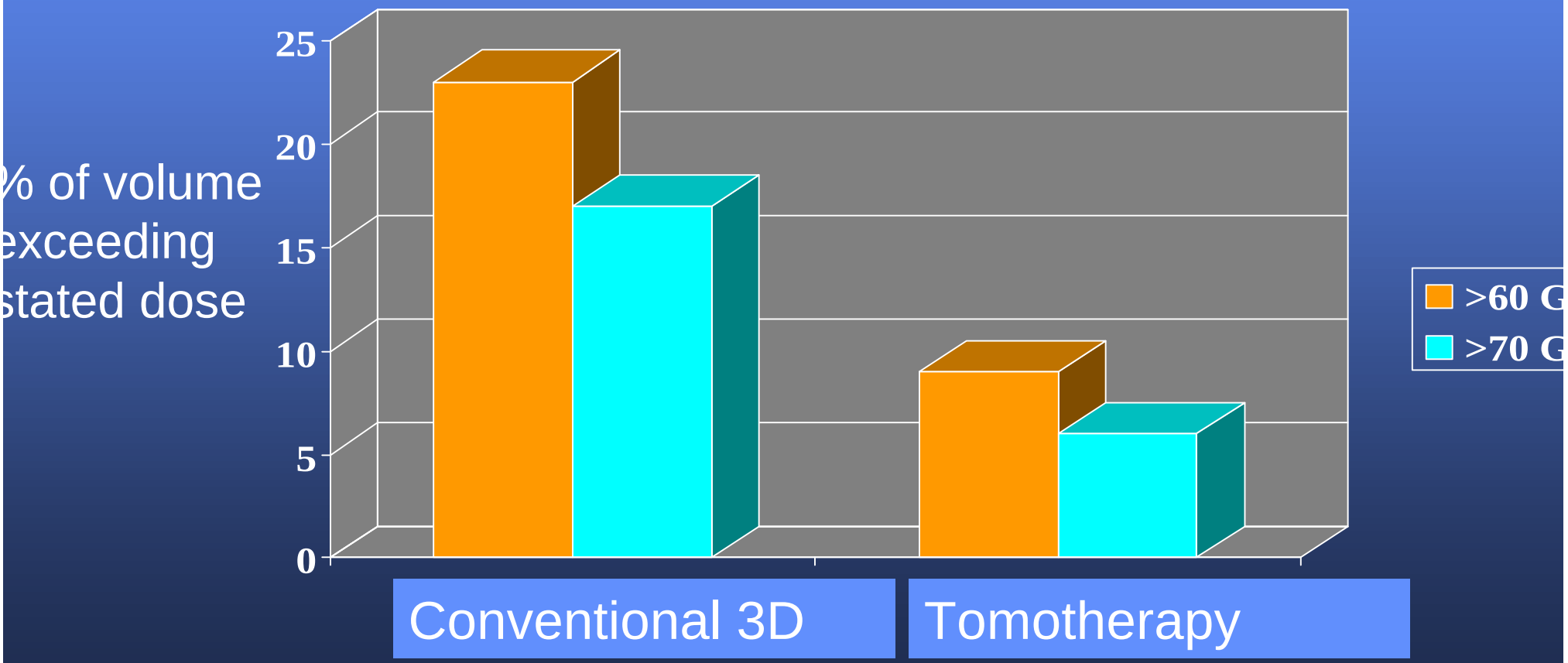
Prostate Carcinoma

Dose Rate **Cumulative Dose**



0 to 30% | 30 to 90% | 90 to 100%

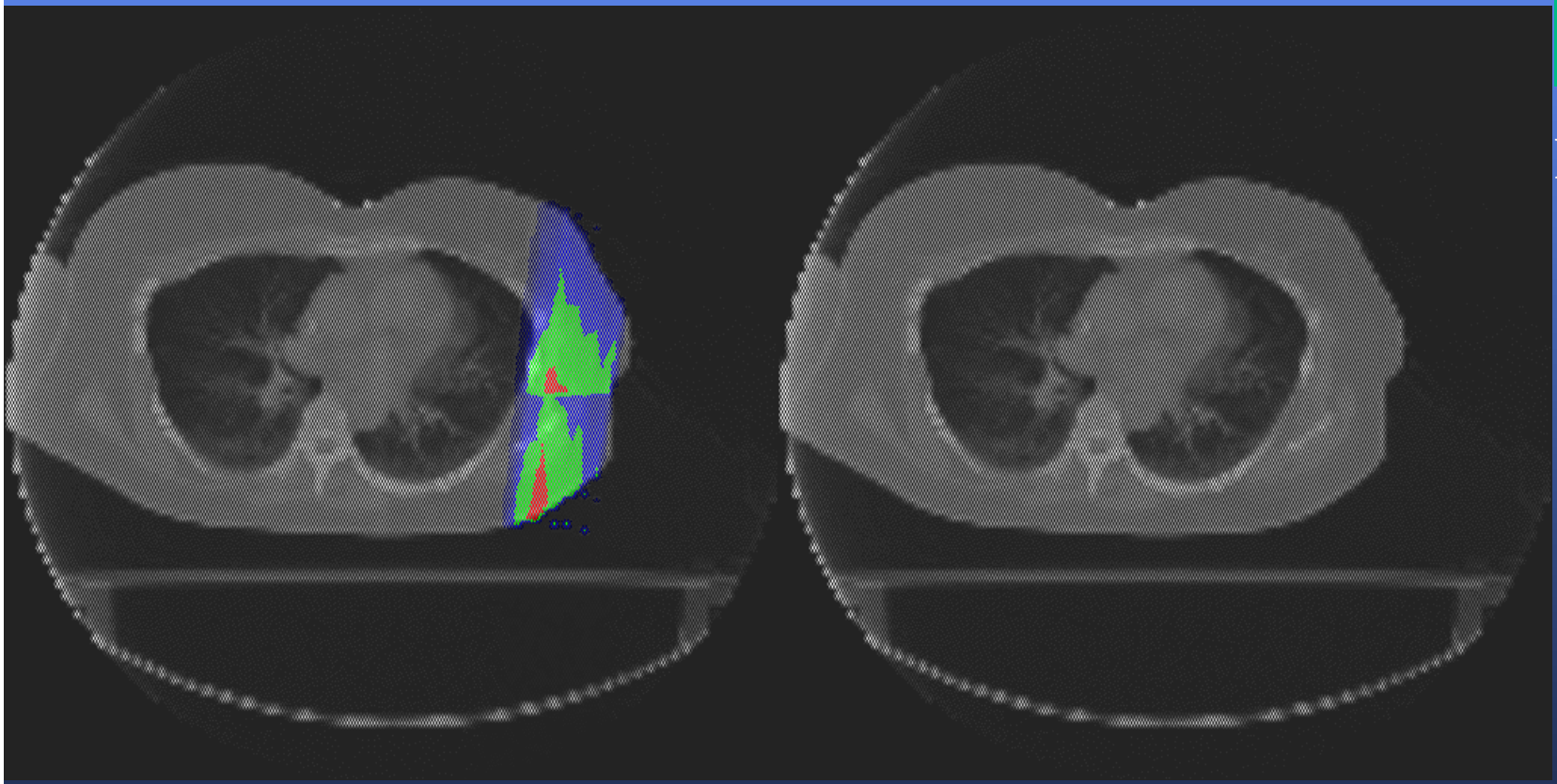
Percentage of Rectal Volume Receiving High Doses

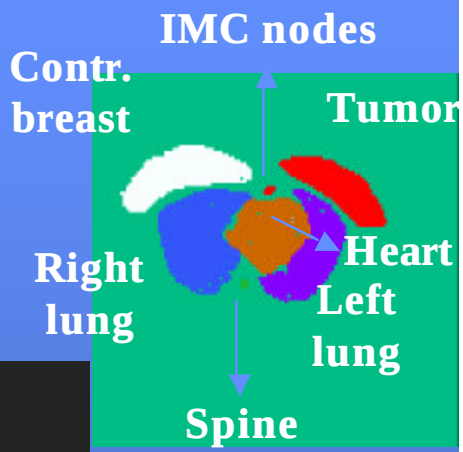


Breast Carcinoma Case: Tomotherapy Movie

Dose Rate

Cumulative Dose





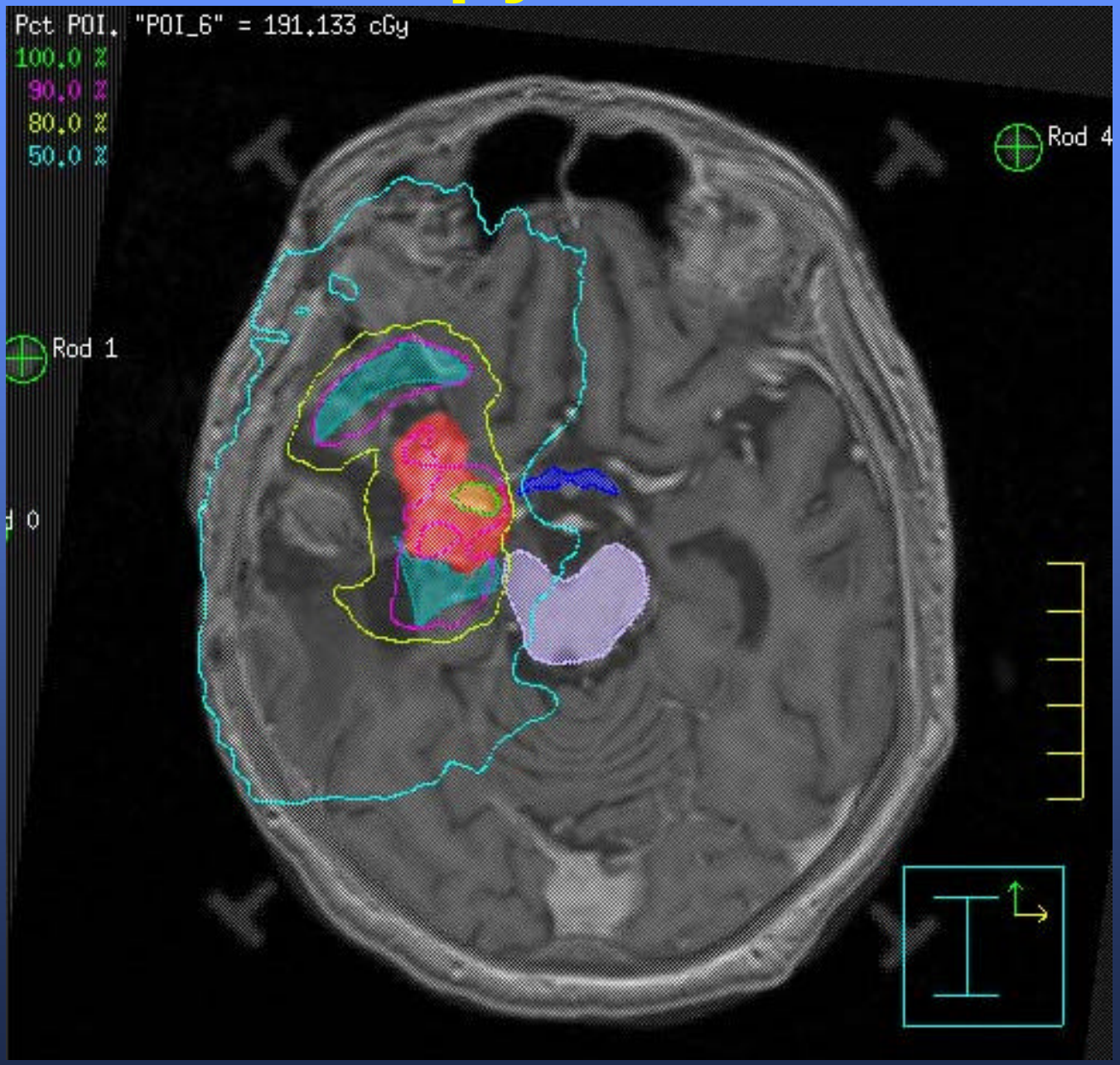
ROI slice 47

0 to 30%

30 to 90%

90% or higher

Tomotherapy for GBM Treatments



Isodose Lines

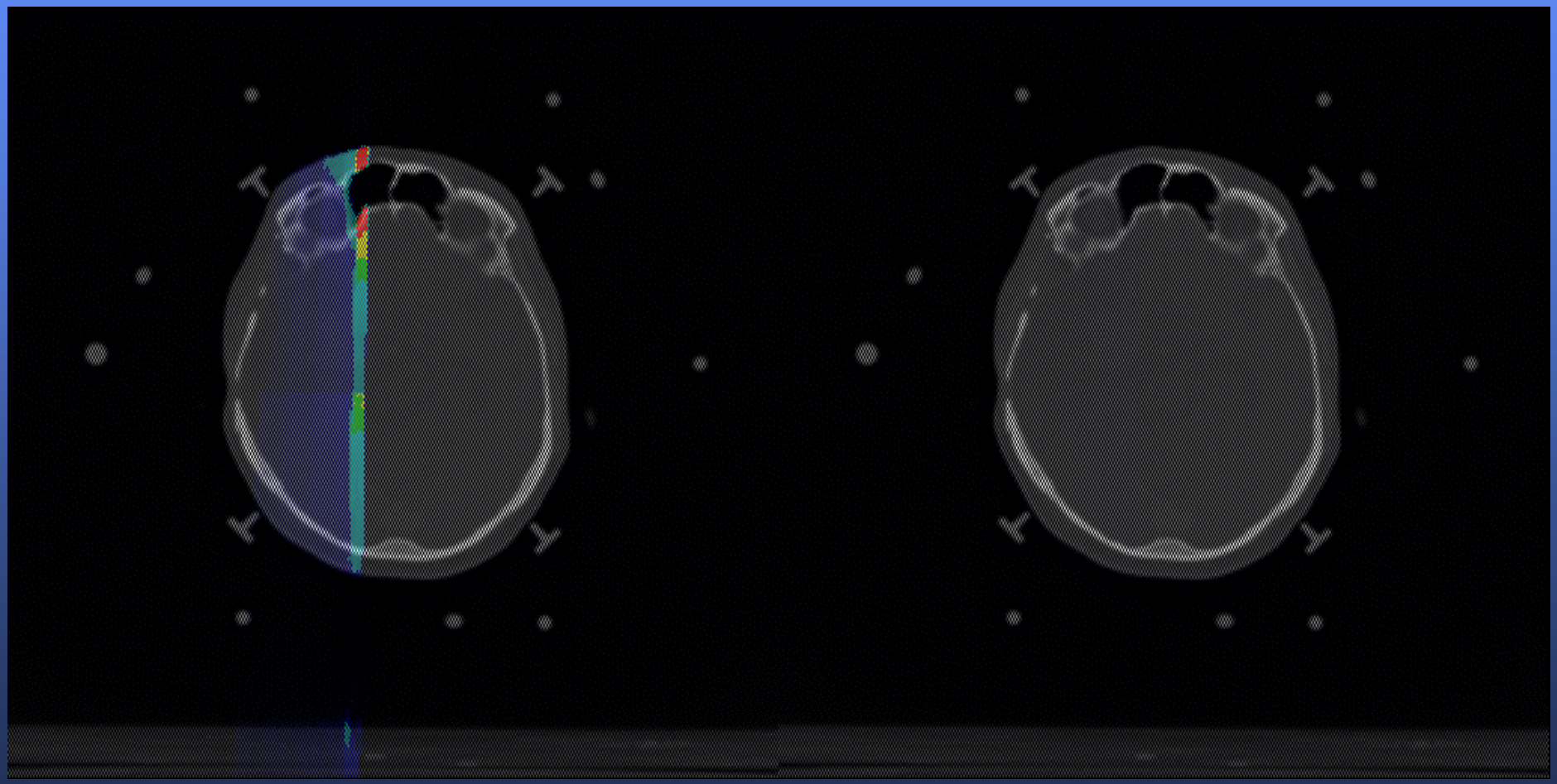
- 100%
- 90%
- 80%
- 50%

Targets

- GTV
- Hypoxic
- Proliferative

Tomotherapy for GBM Treatments

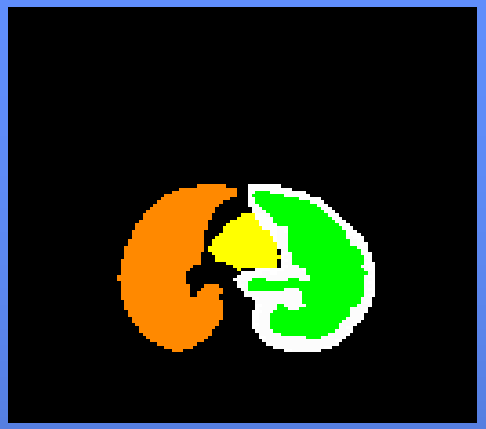
Dose Rate **Cumulative Dose**



0 to 50 % | 50 to 75% | 75 to 85 % | 85 to 95 % | 95 to 100%

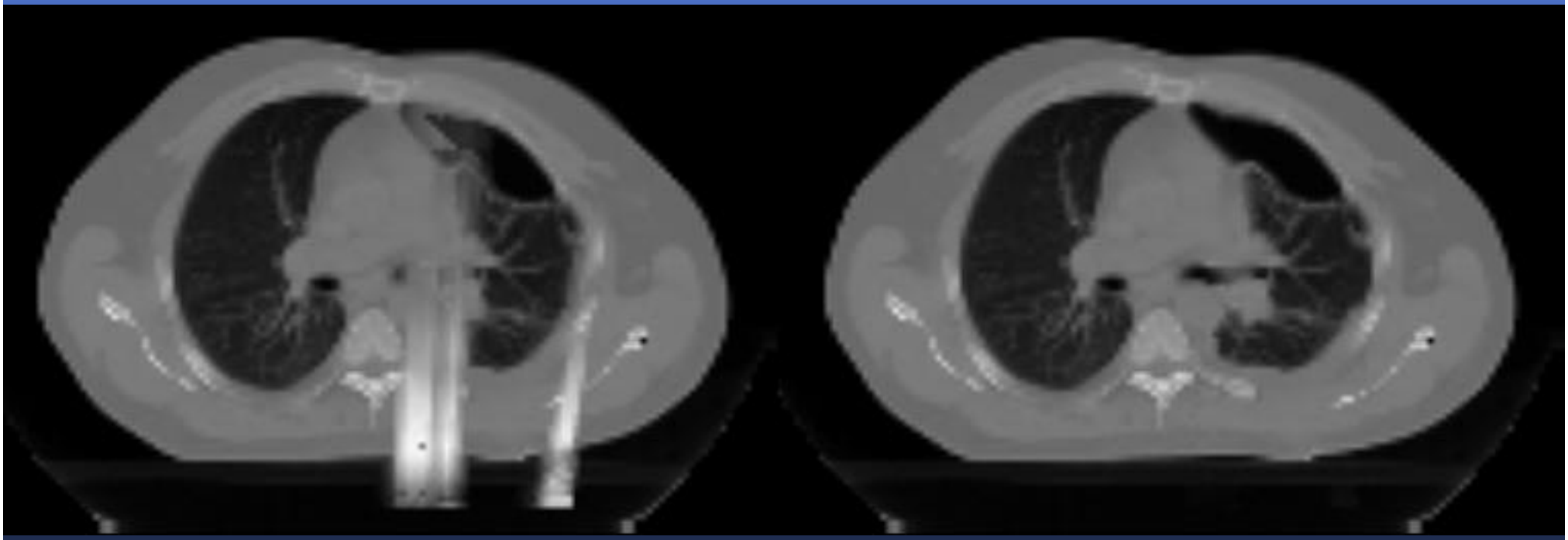
Mesothelioma

ROI slice 27

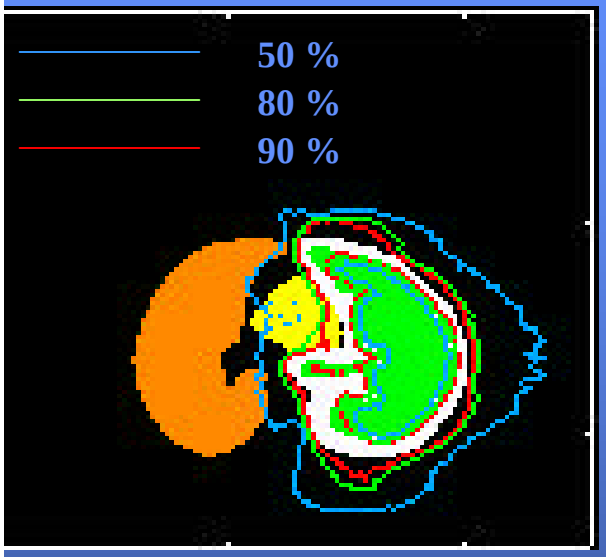


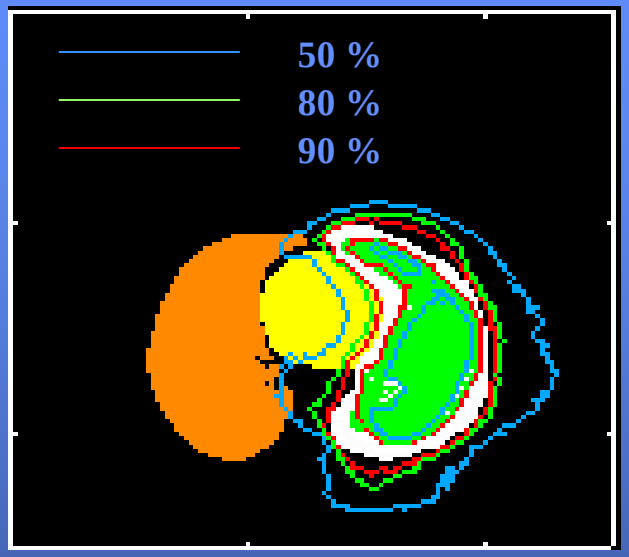
Dose Rate

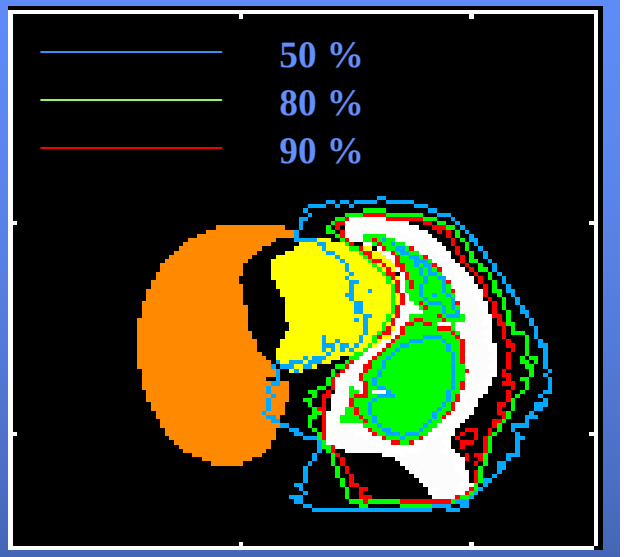
Cumulative Dose

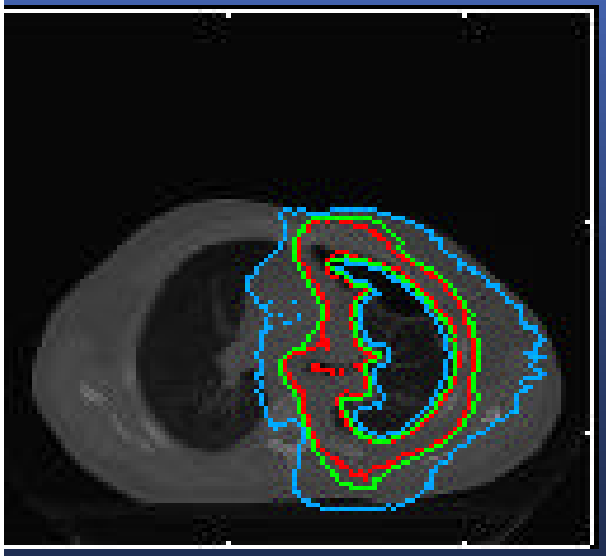


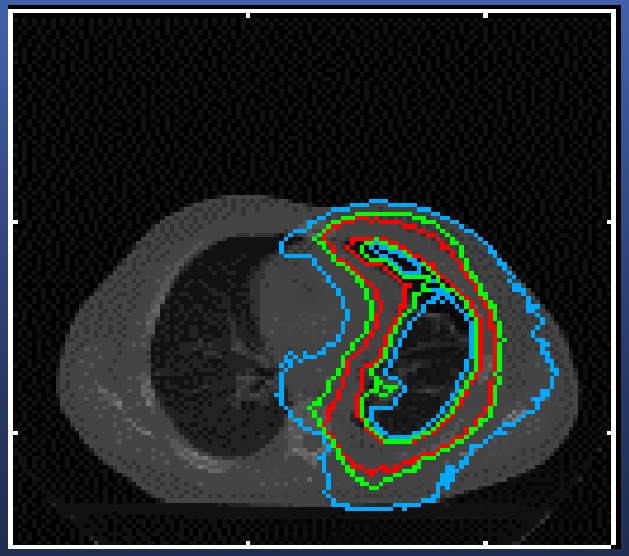
Tomotherapy Dose Distributions

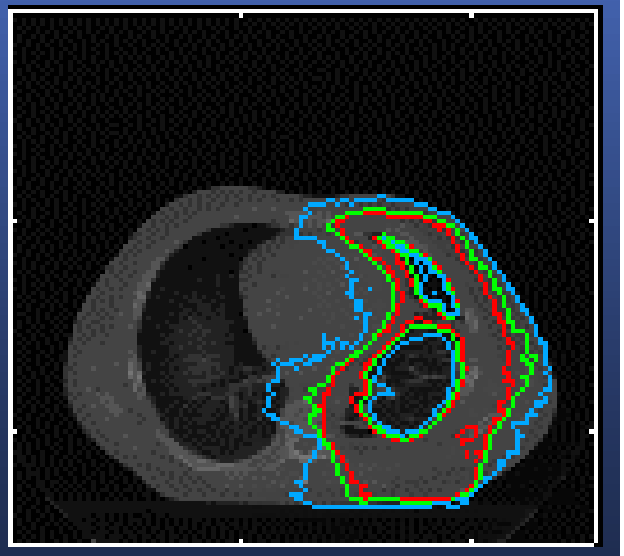


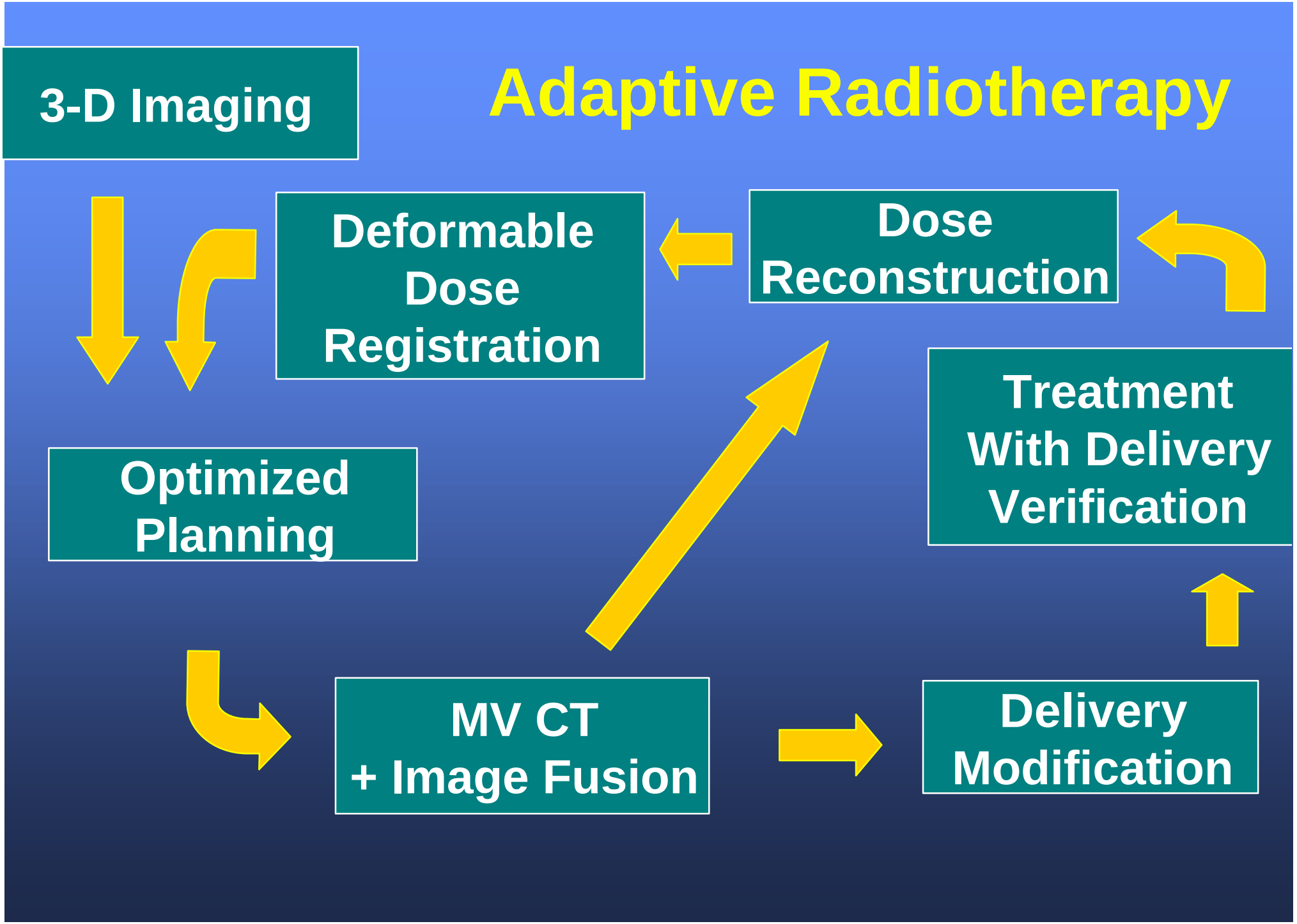










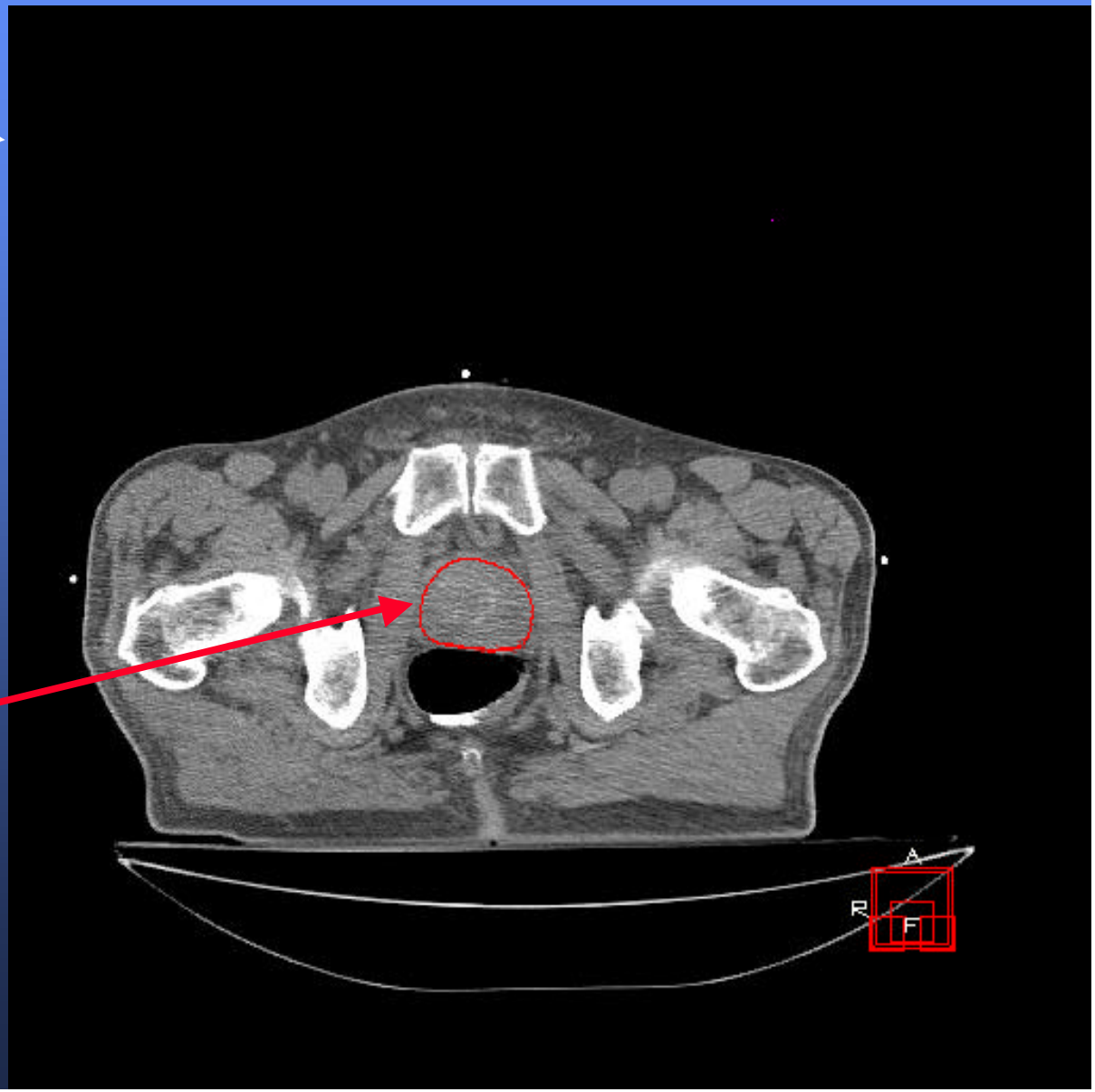

Adaptive Radiotherapy
3-D Imaging
Deformable Dose Registration
Dose Reconstruction
Optimized Planning
Treatment With Delivery Verification
MV CT + Image Fusion
Delivery Modification

Why CT Before Delivery is Necessary

CT Images Acquired Daily

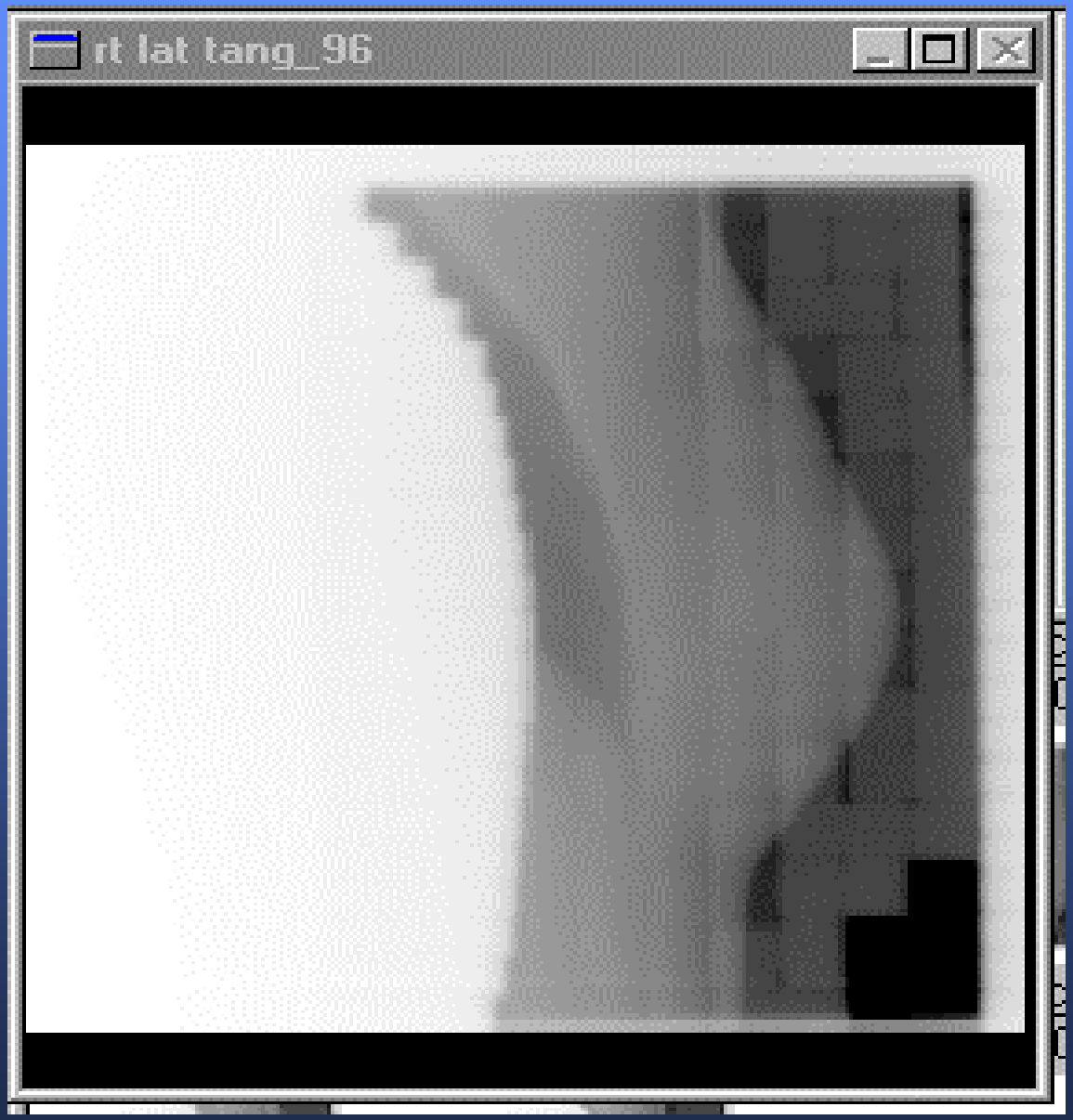
The slices were rotated and translated to align the bony anatomy as best as possible.

Original CTV



Courtesy Di Yan and Marcel Van Herk

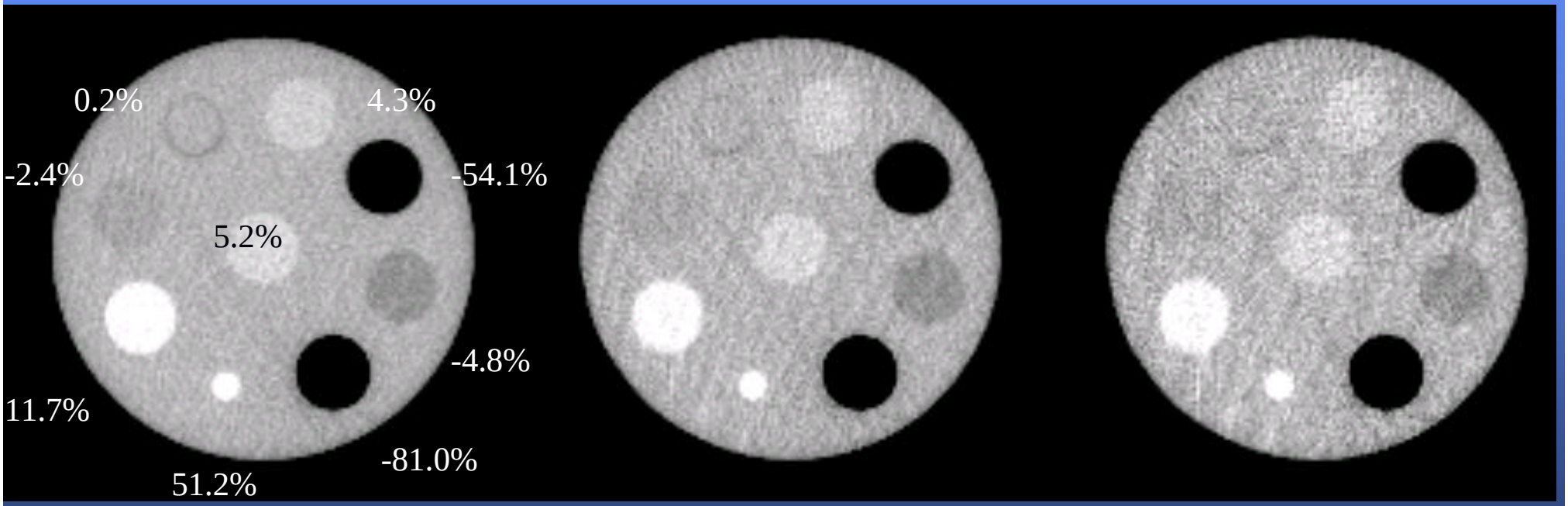
Interfraction Movement of the Breast



Electronic portal image of the breast treated using a compensator. Each frame is a different day.

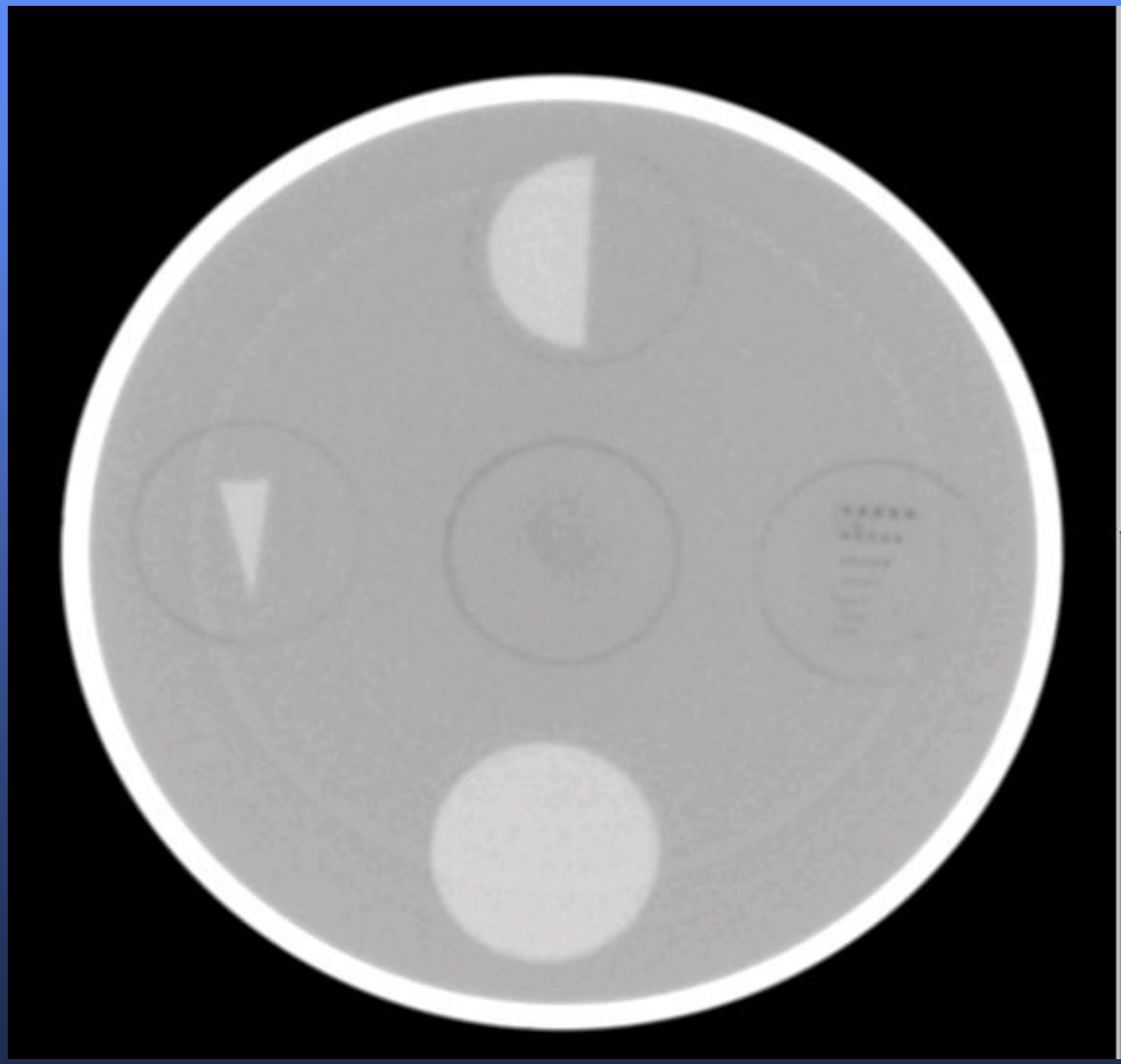
From Dr. Jason Sohn Mallinckrodt Institute

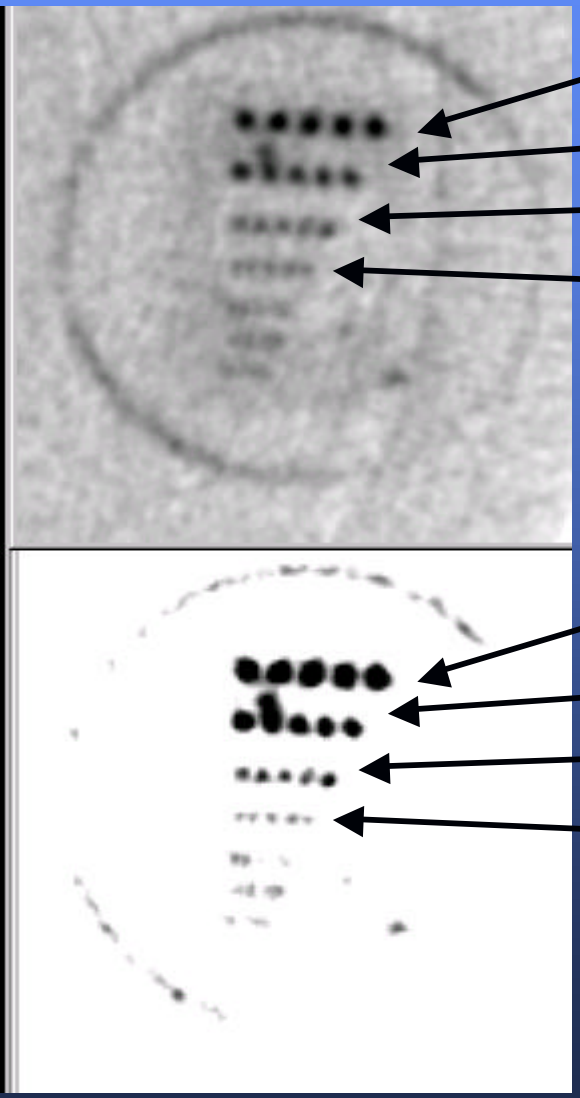
MVCT of CIRS Phantom



7 cGy **3.5 cGy** **1.75 cGy**

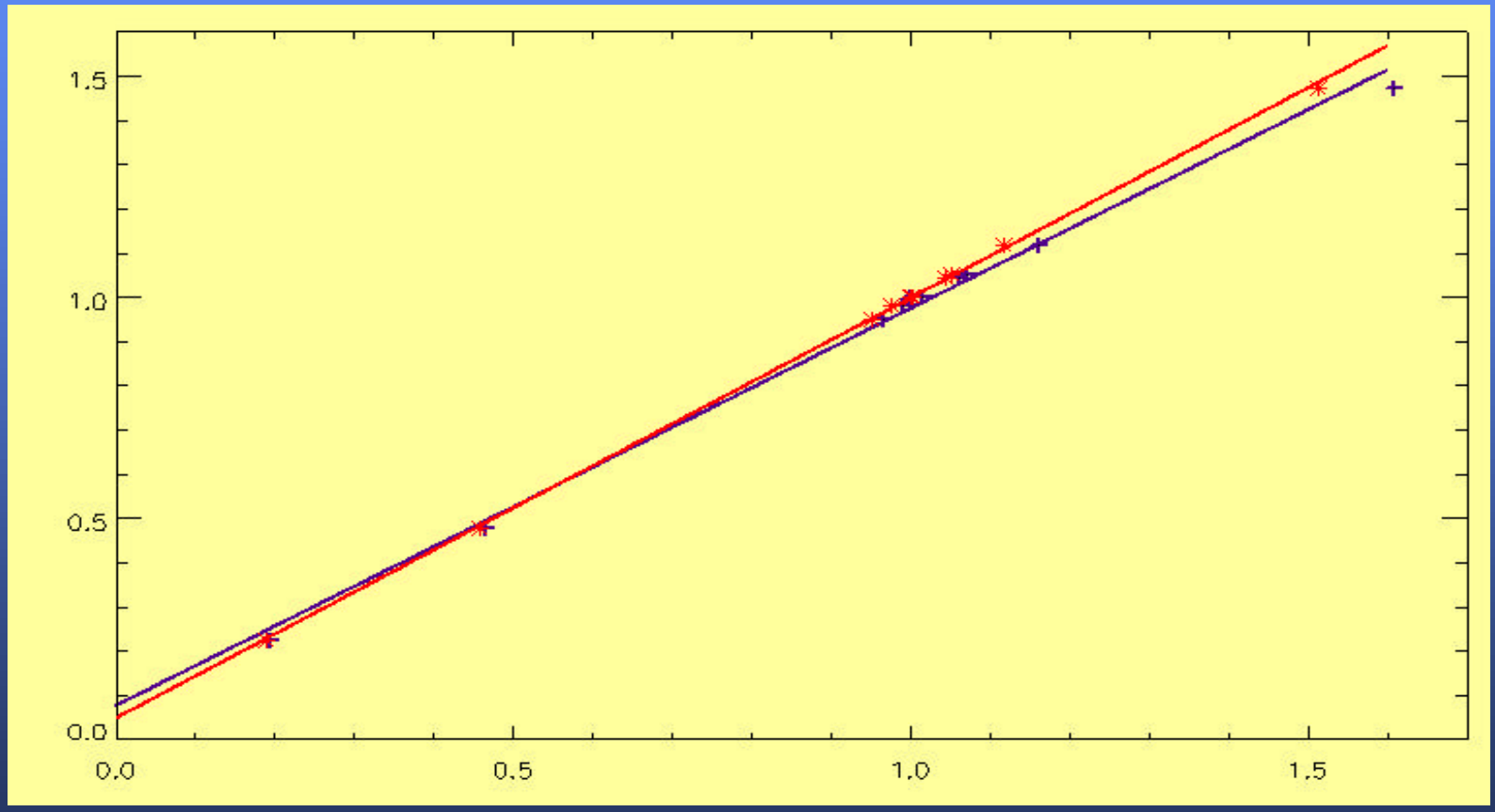
MVCT of RMI Phantom





MVCT Calibration Curve

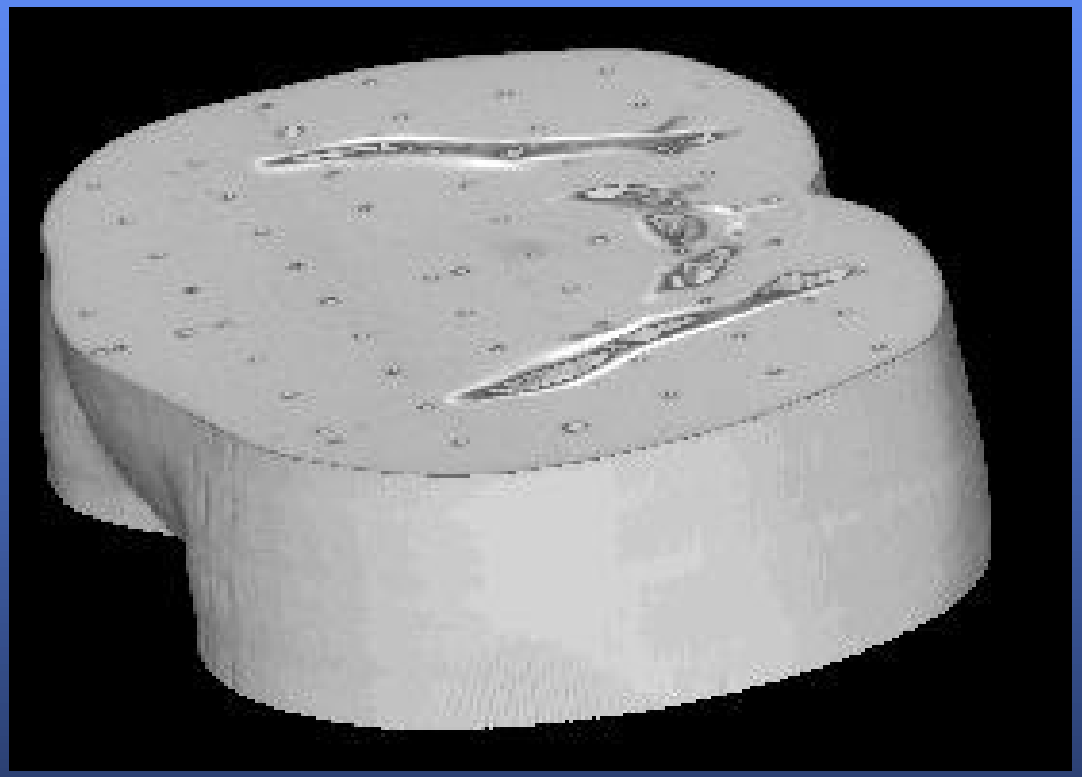
Image Density



Electron density (red), physical density (violet)

Rando Phantom Megavoltage CT (MVCT)

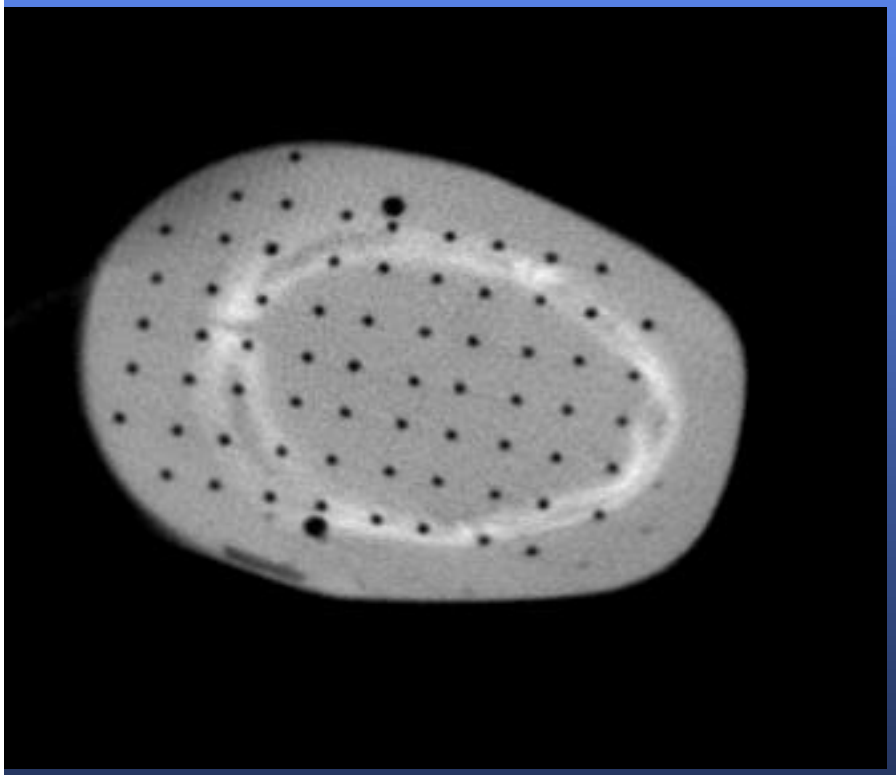
Head



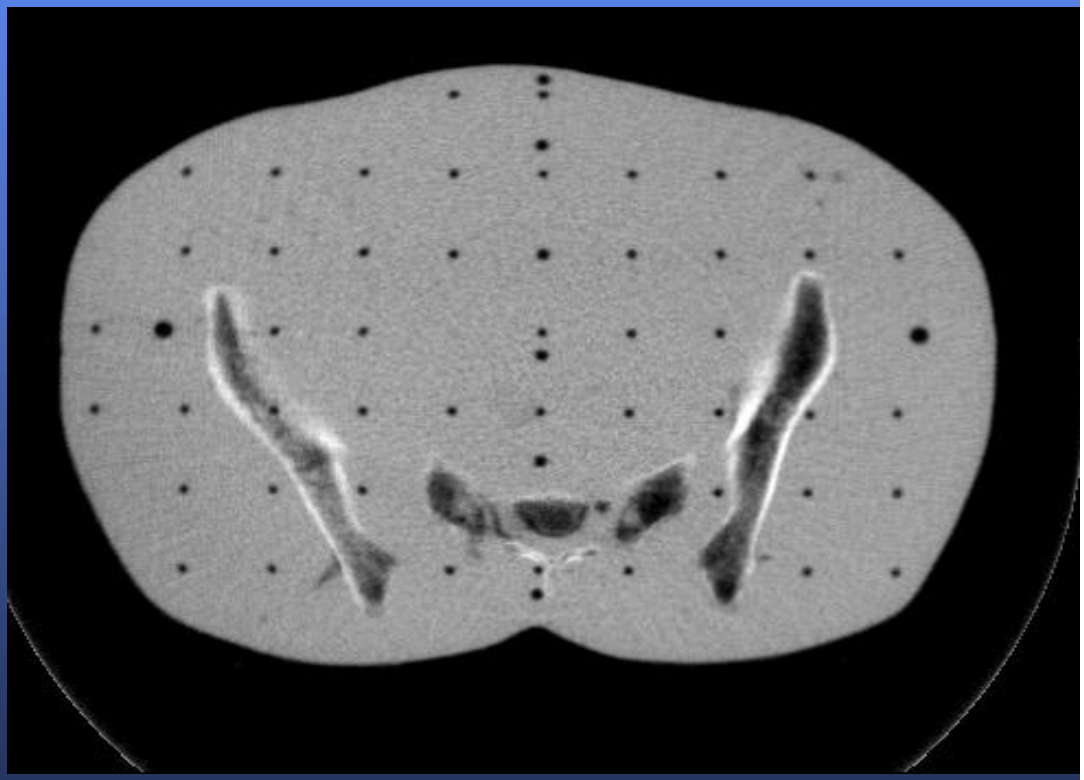
Pelvis

Rando Phantom MVCT

Slice-by-Slice Traversal Through Volume

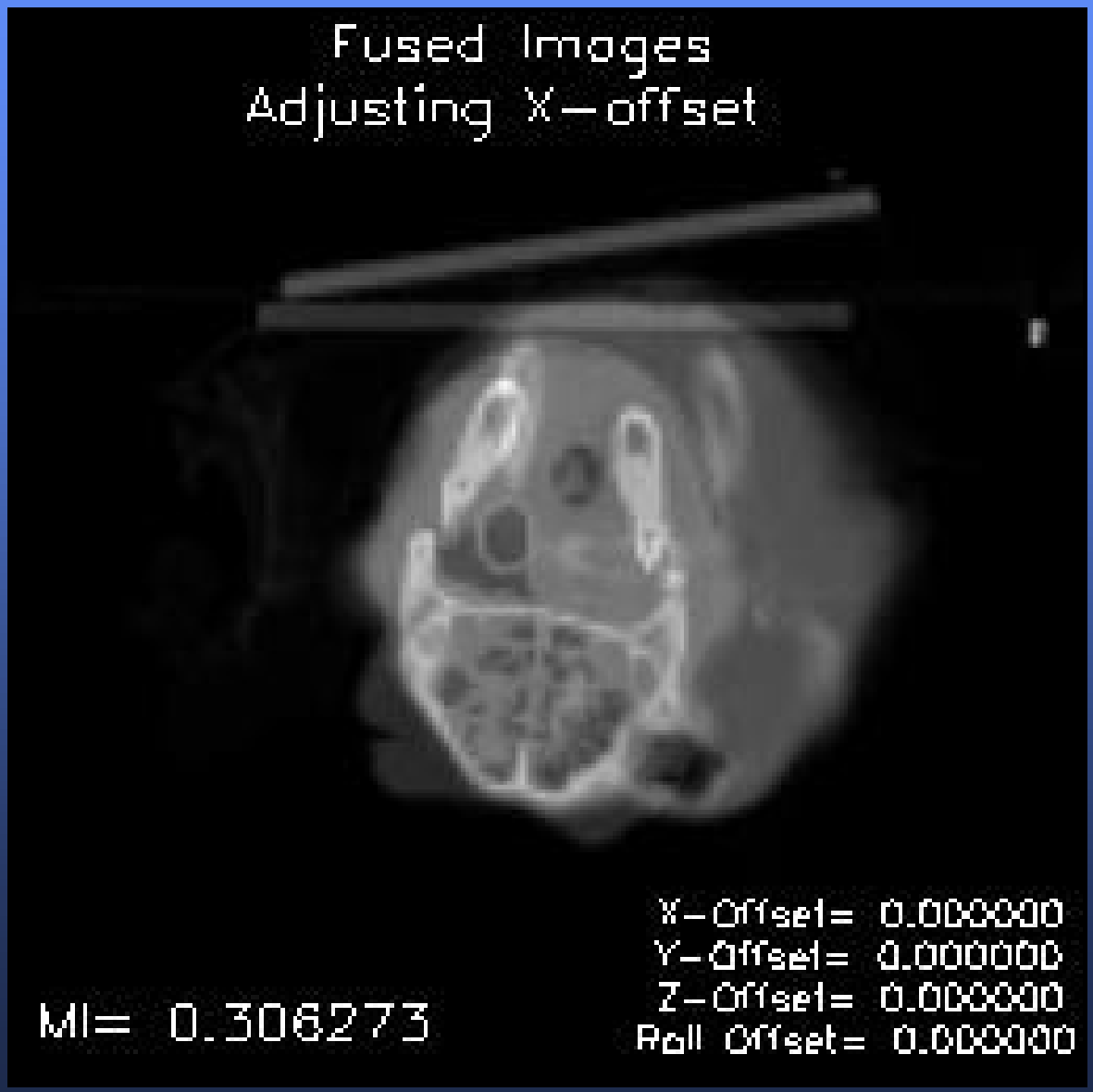


Dose for Scan = 3 cGy

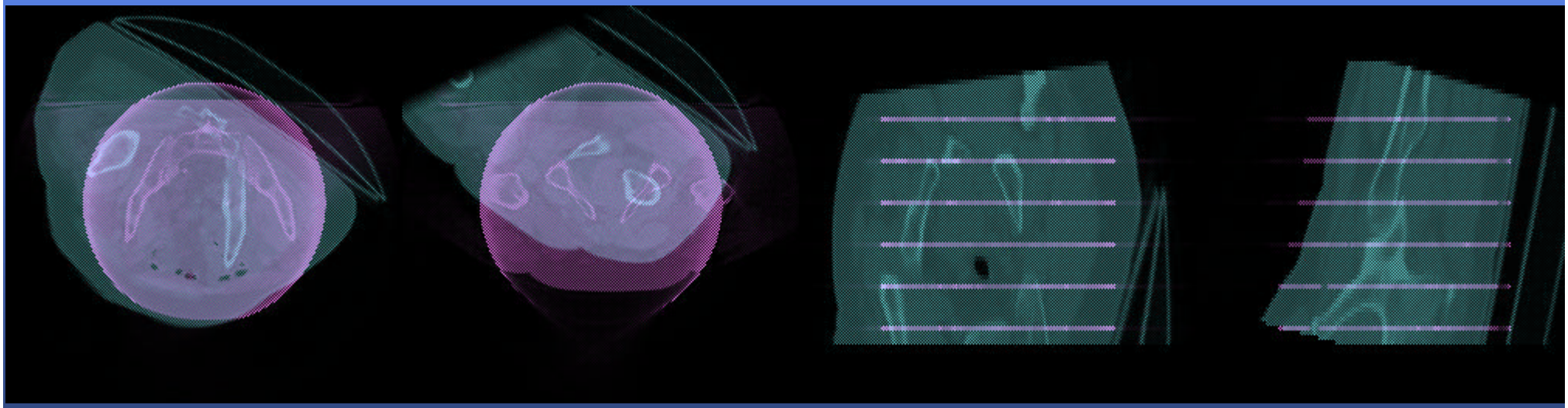


Dose for Scan = 5 cGy

Automated Fusion of kV and MV CT Sets



Fusing Prostate CT's Acquired on Two Different Days



X-offset= 4.20 cm

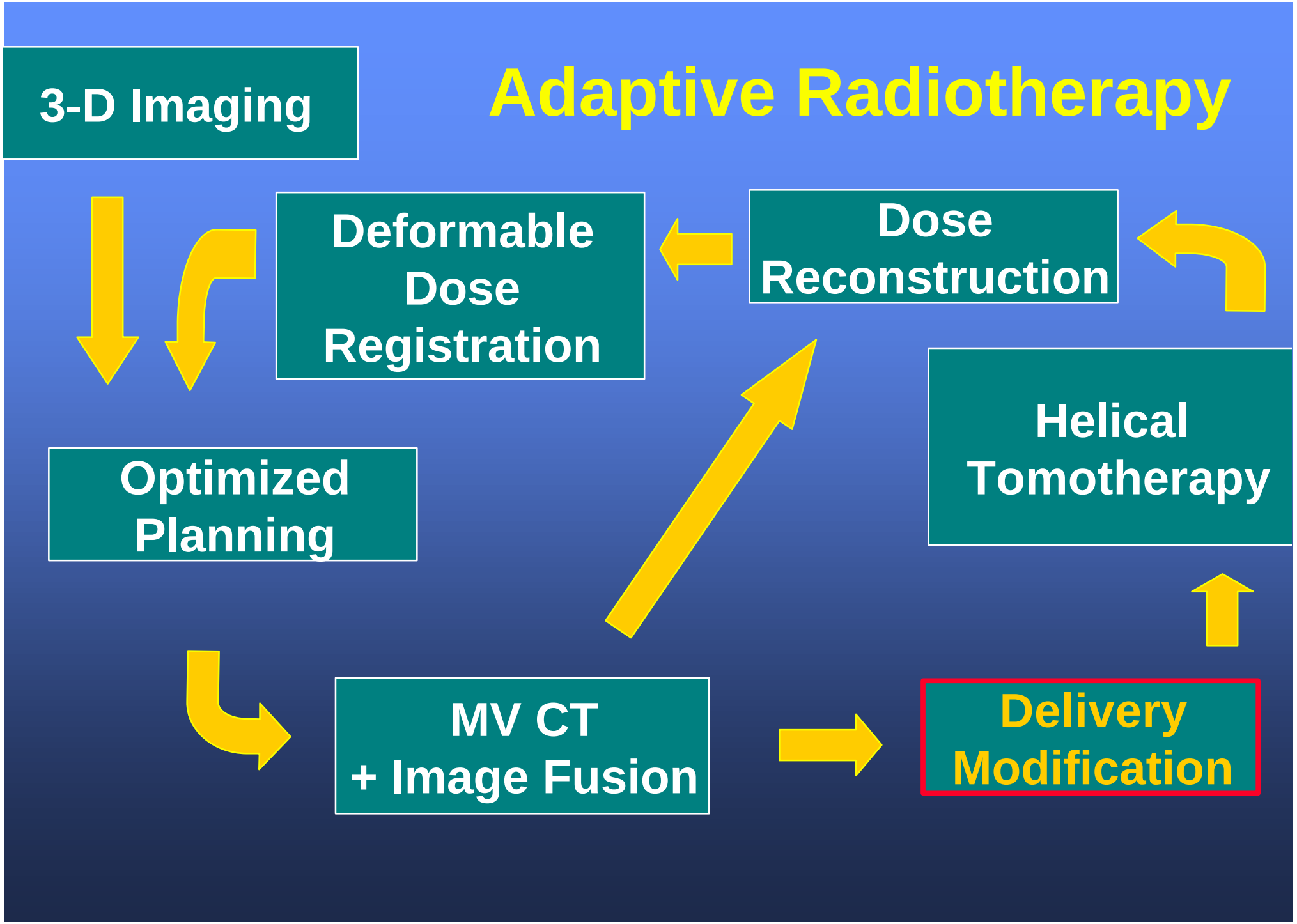
Y-offset= 4.20 cm

Z-offset= 2.60 cm

Roll-offset= 32.50 deg

Pitch- offset= 8.90 deg

Yaw- offset= 14.70 deg


3-D Imaging
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Helical Tomotherapy
MV CT + Image Fusion
Delivery Modification

Delivery Modification

- There are two potential ways to adjust the patient setup:
  - Adjust the patient.
  - Adjust the beams.
- It may be easier and more reliable to move the beams to the patient.
- It may be possible in tomotherapy to alter the leaf delivery pattern.

Optimized

50 %
80 %
95 %

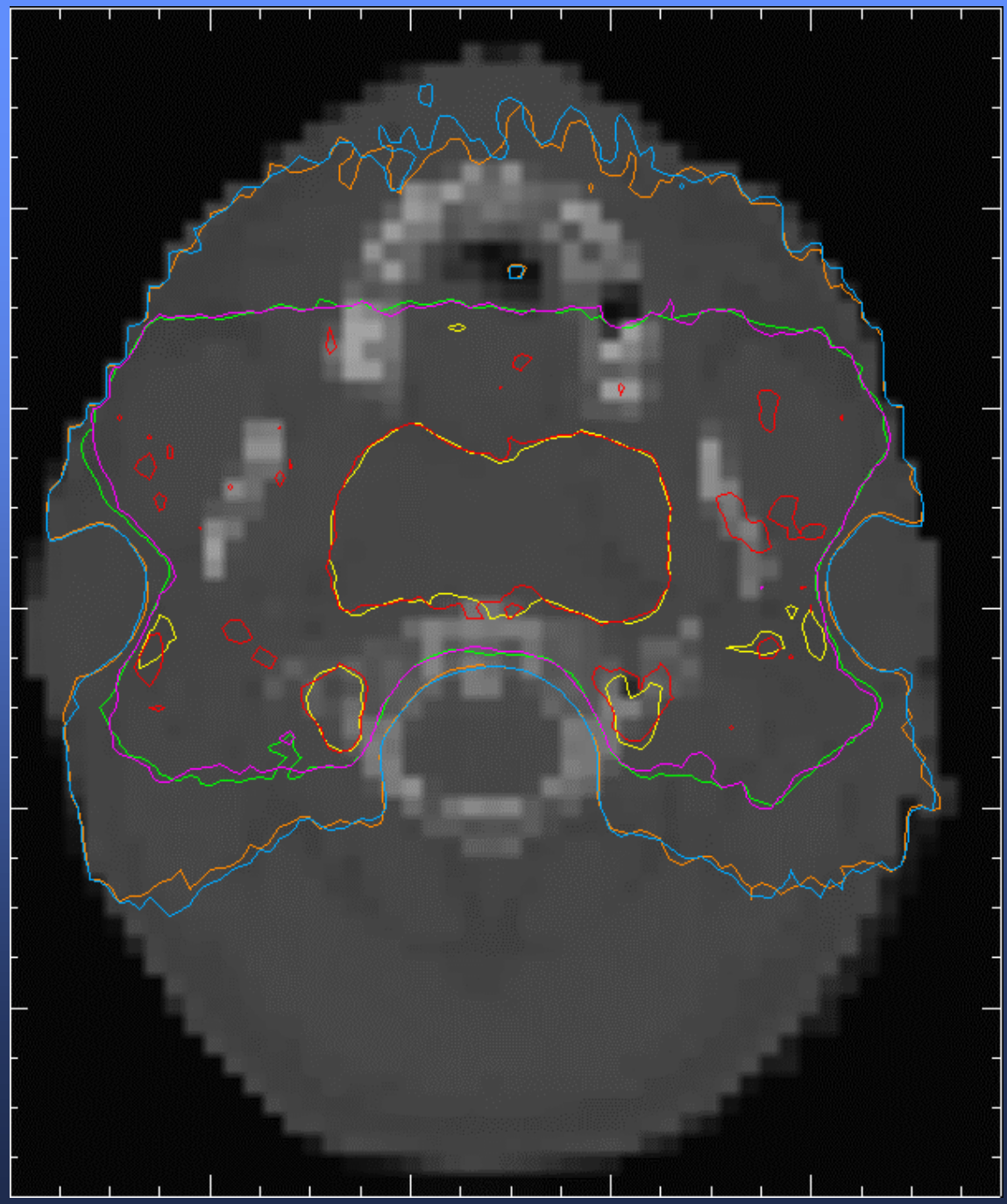
Delivery Modified

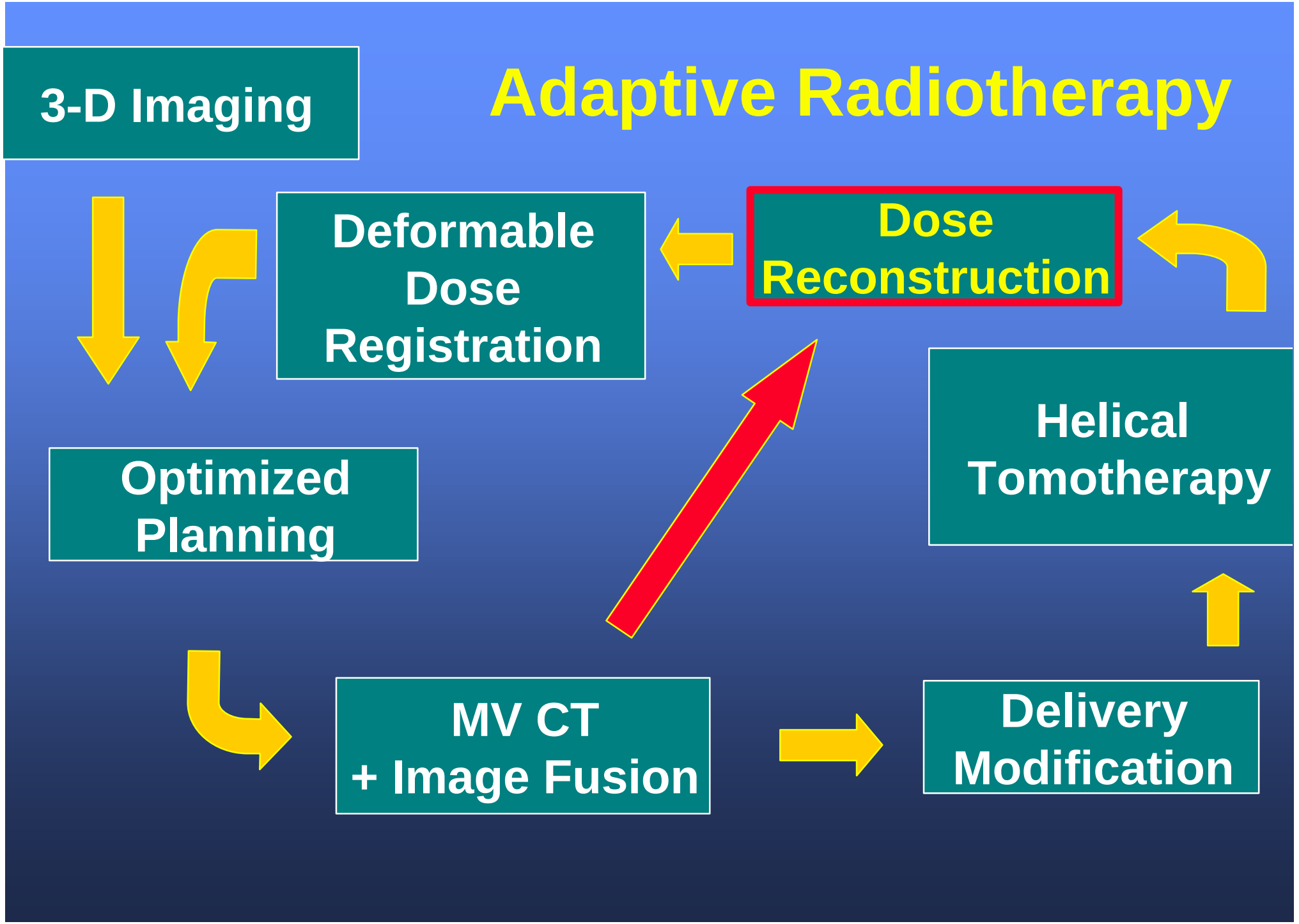
50 %
80 %
95 %

1.42 cm offset

1cm x-offset

1cm y-offset

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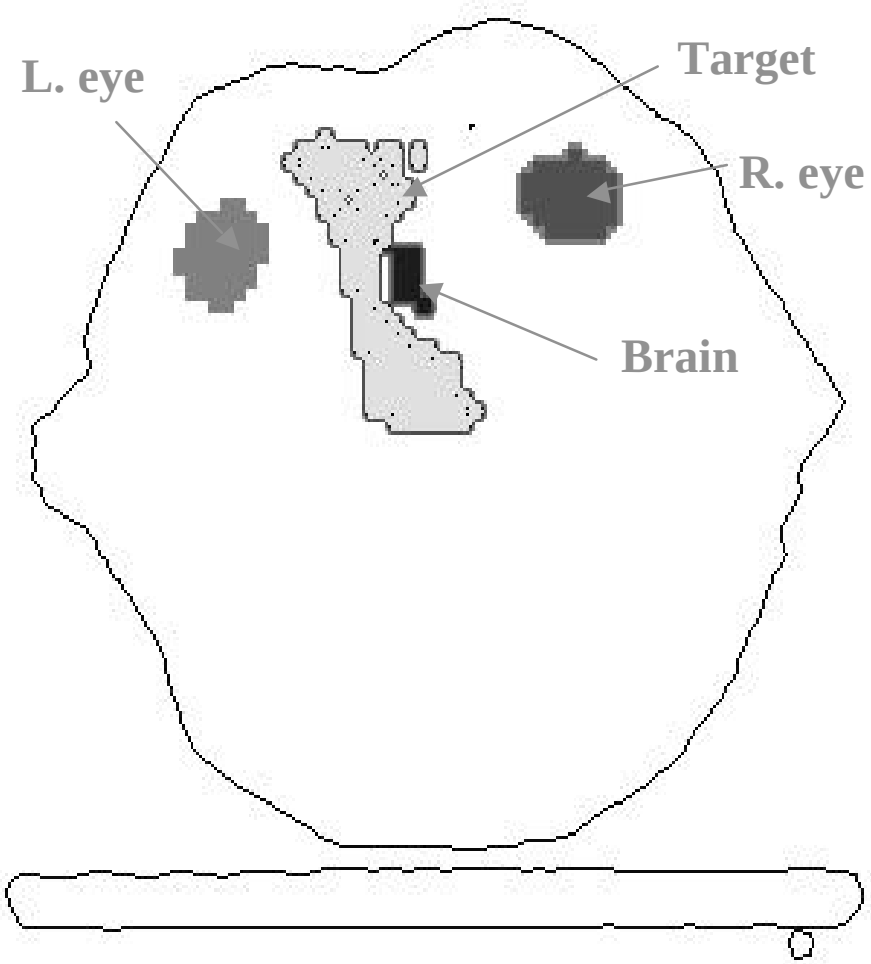
Dose Reconstruction

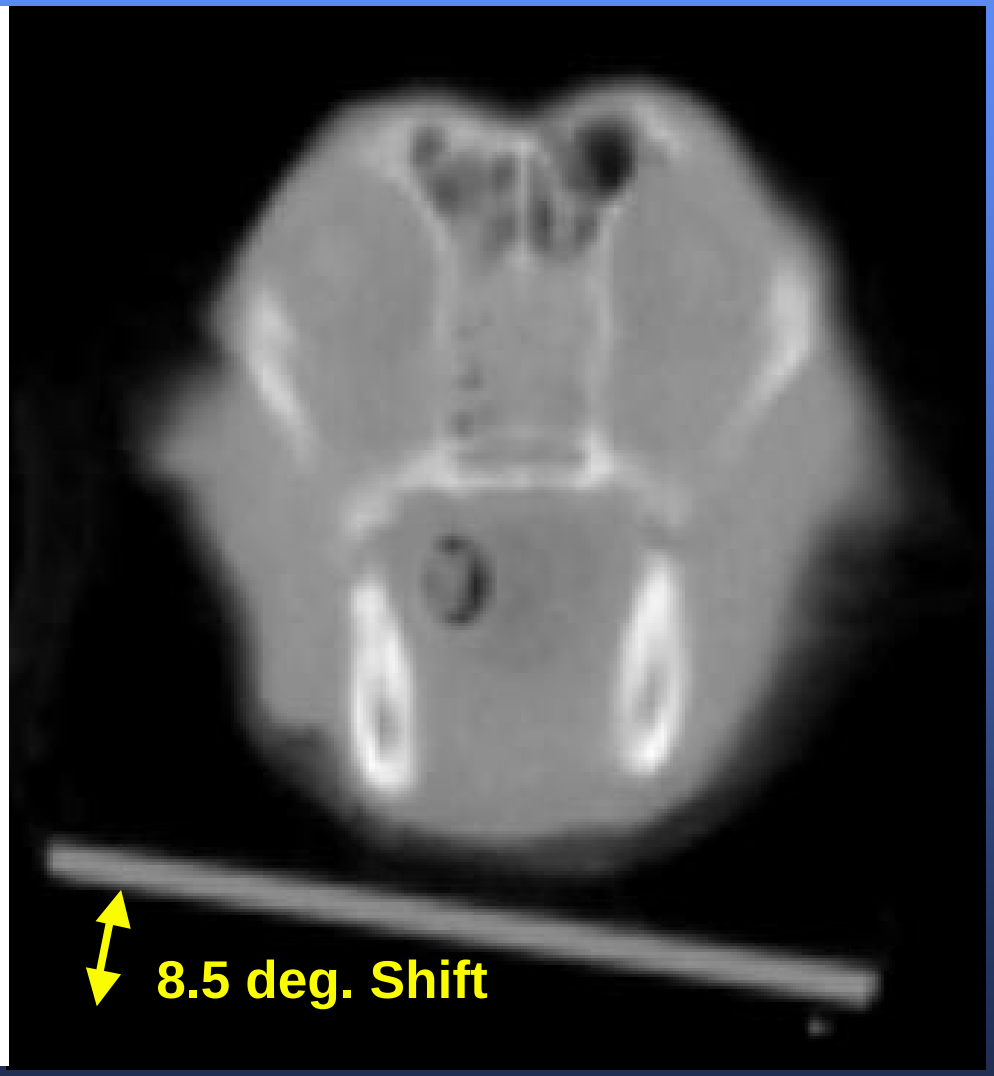
- Dose reconstruction uses transmission data acquired during treatment and the megavoltage CT to determine the dose distribution delivered that day.
- Dose reconstruction provides a way to directly compare the plan with the result.

Example of Dose Reconstruction

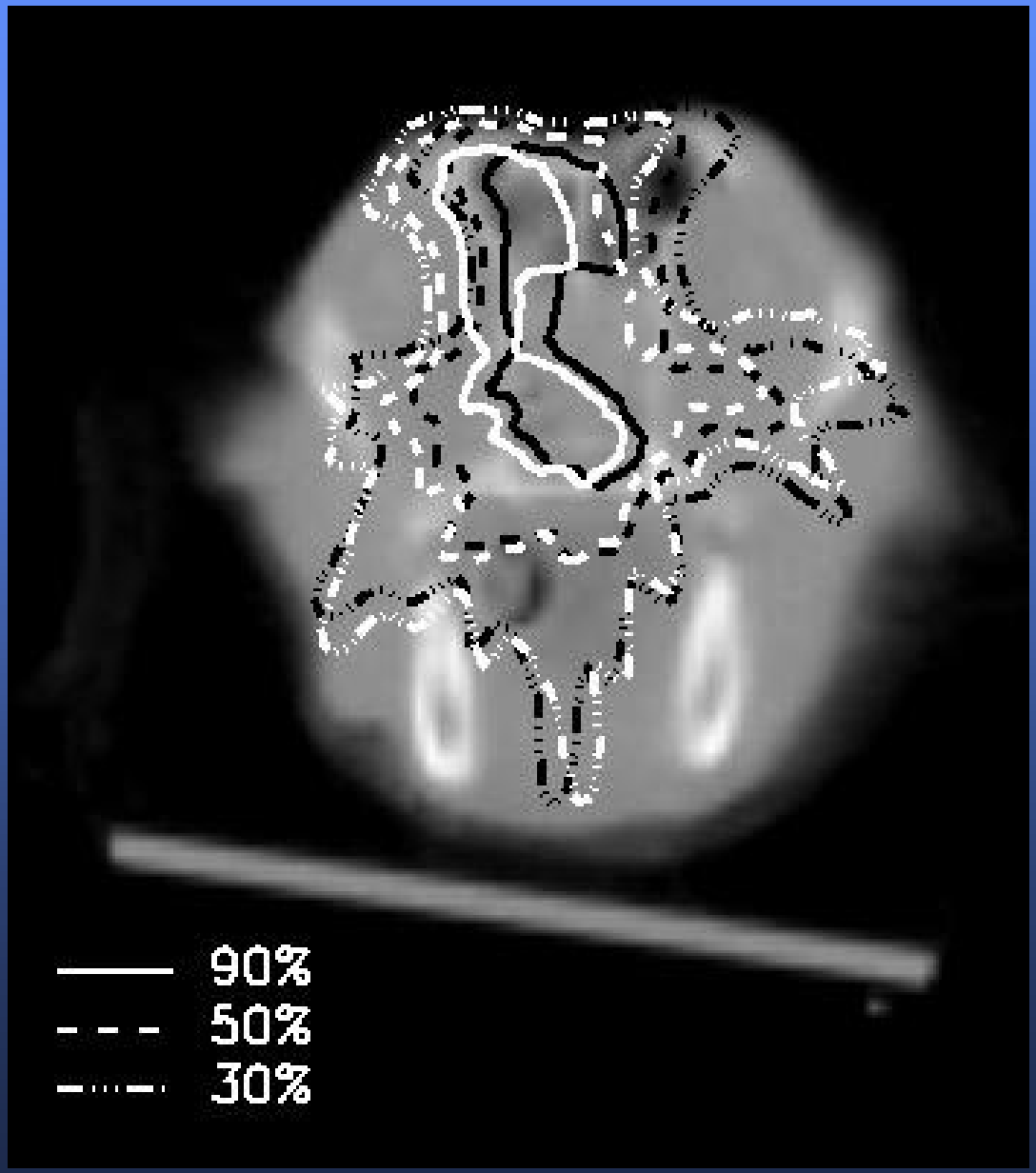
ROI's (slice 29)



MV CT (slice 29)



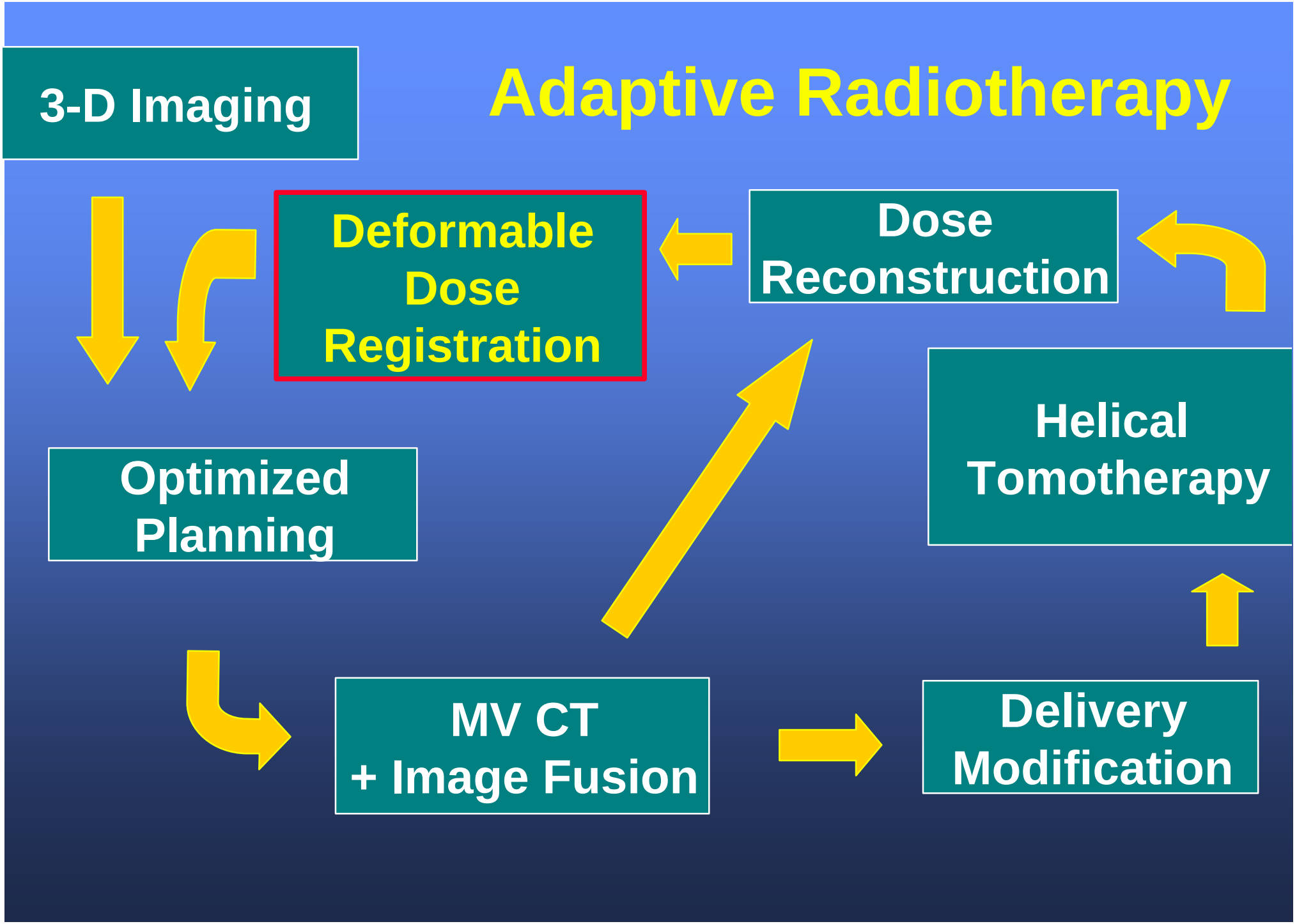
Dose Reconstructed Using MV CT



The reconstructed dose reveals that the dose distribution is rotated toward the left eye and underdosing the target volume.

Optimized

Reconstructed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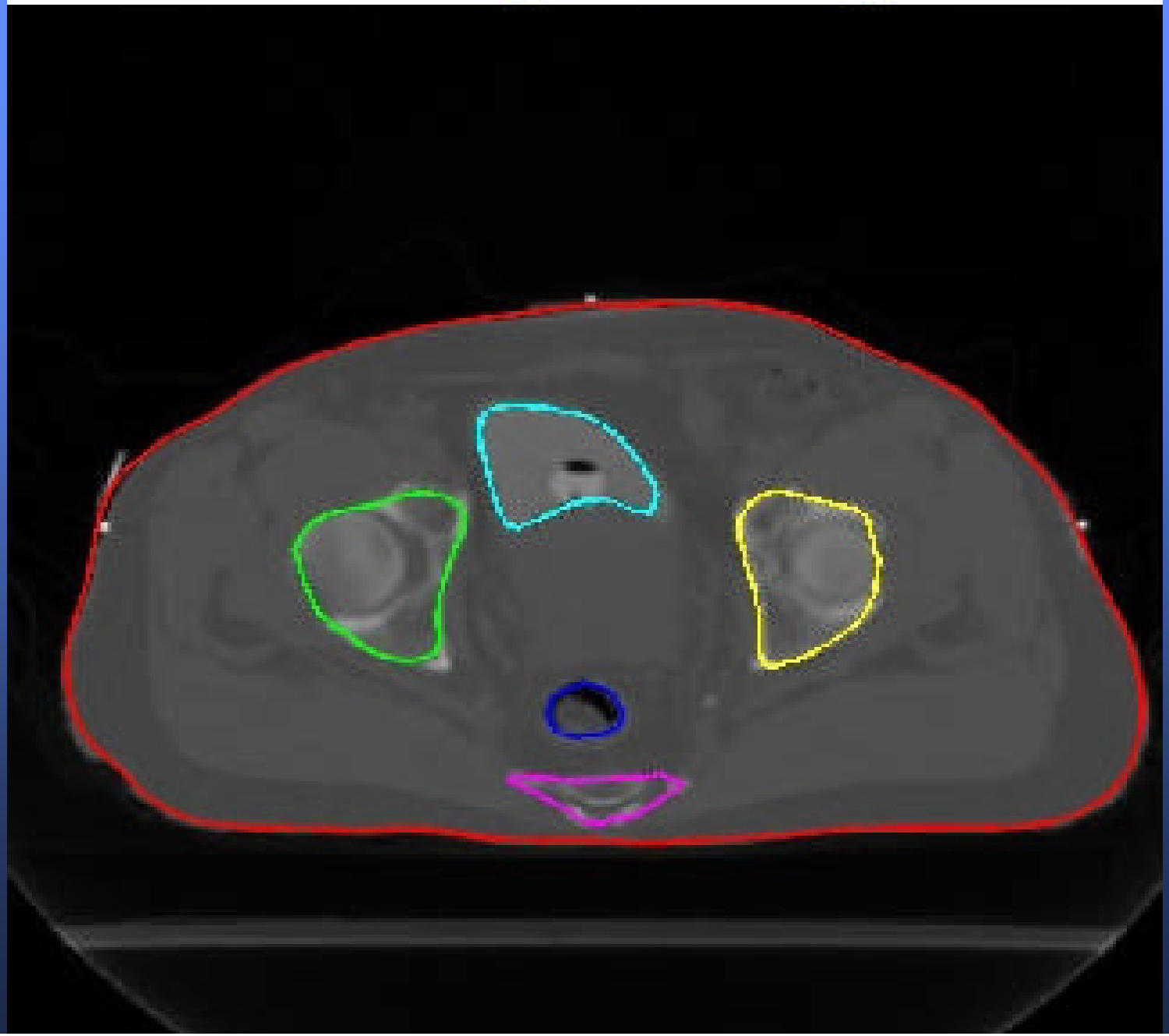
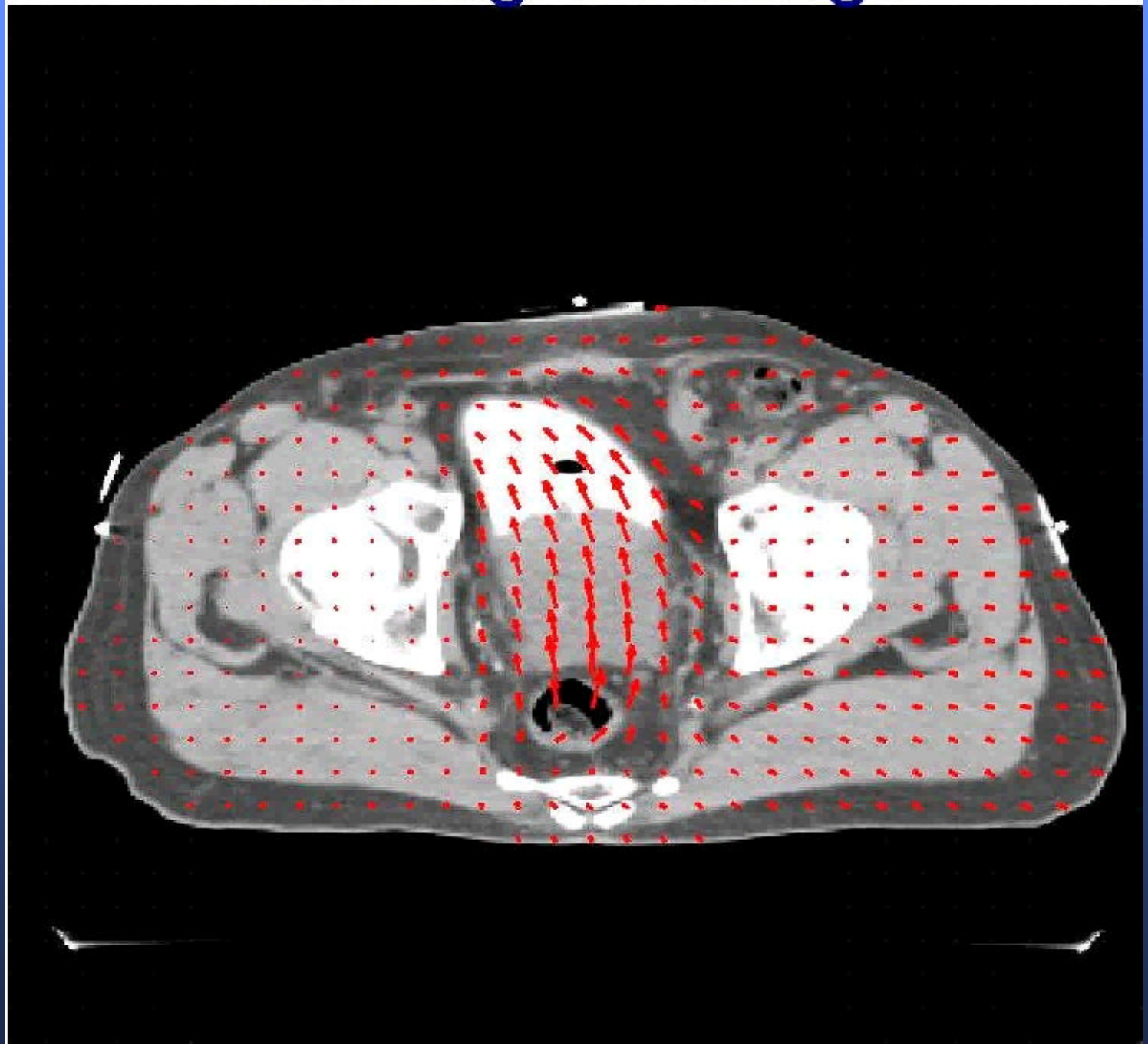
Deformable Dose Registration

- Deformable dose registration uses a mechanical deformation model along with matched contours and points from two image sets to register them.
- Deformable dose registration allows the dose from each fraction to be added up properly.

Planning CT image



Planning CT image



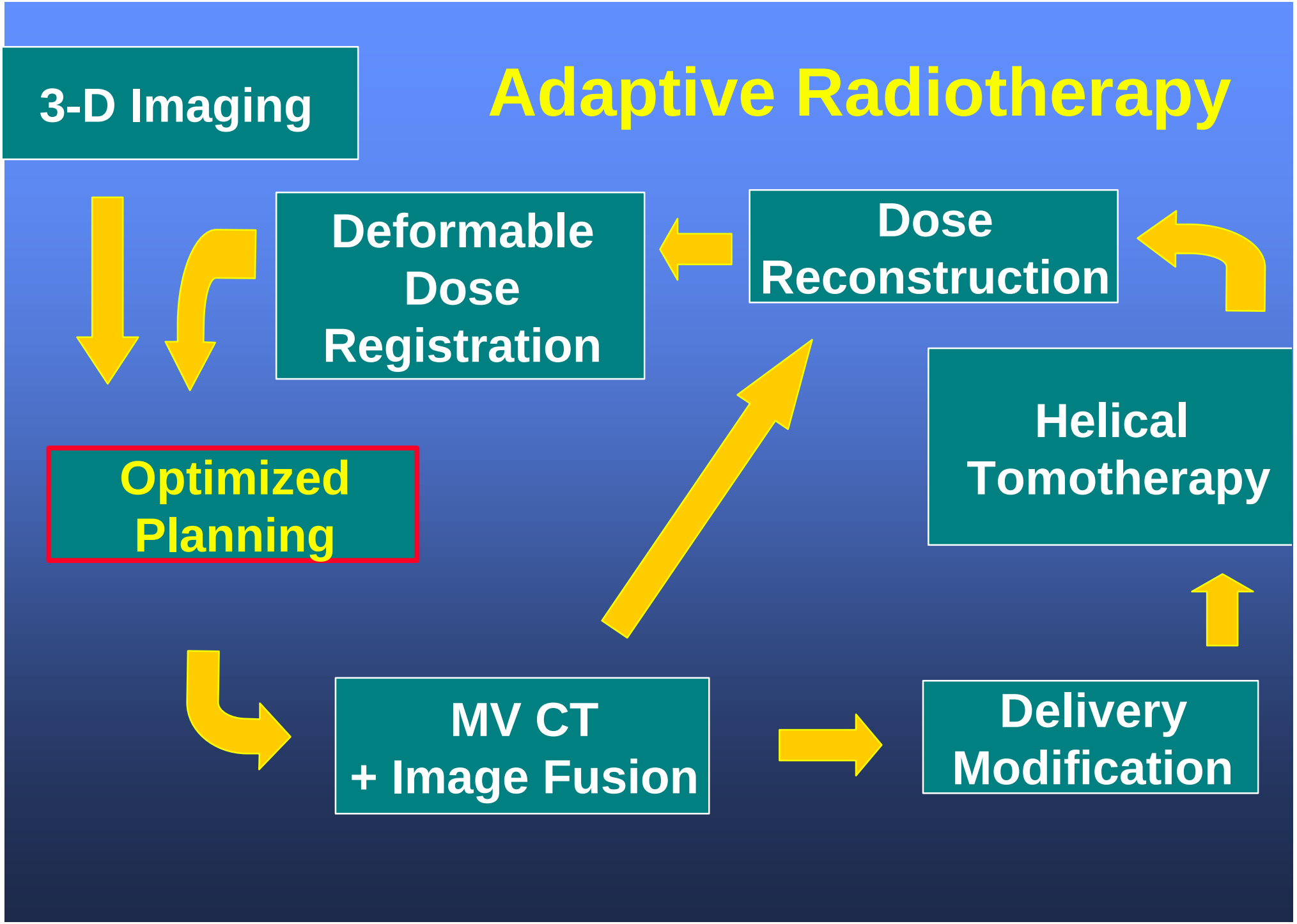

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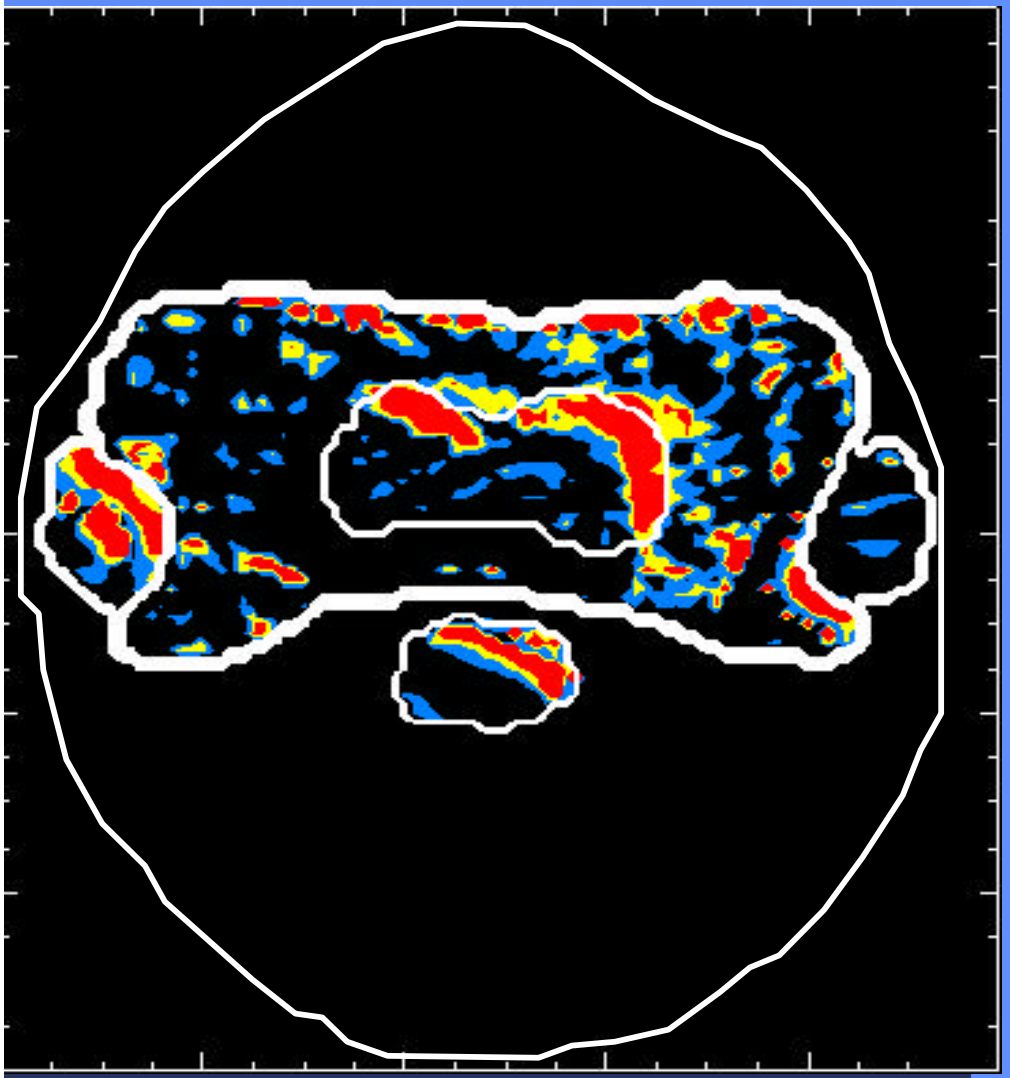
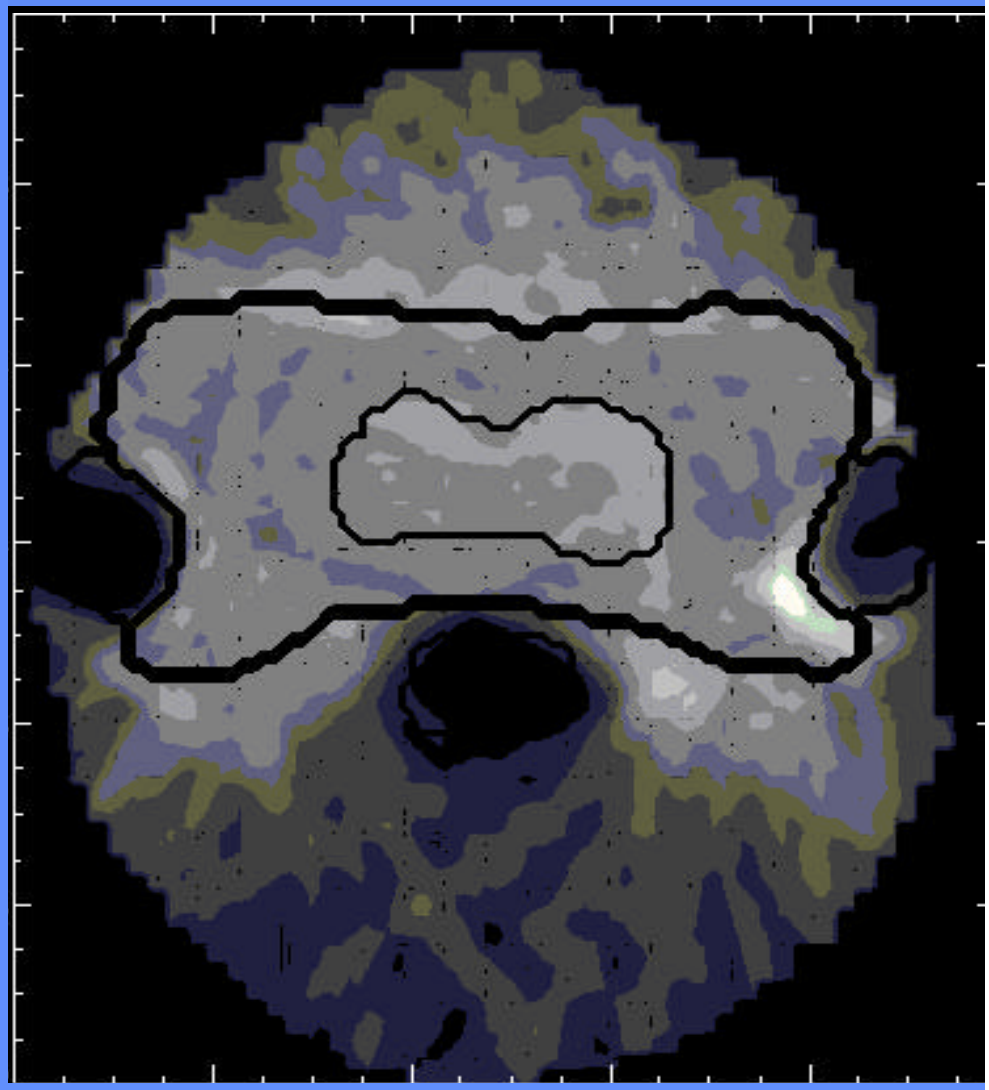
Image of Regret



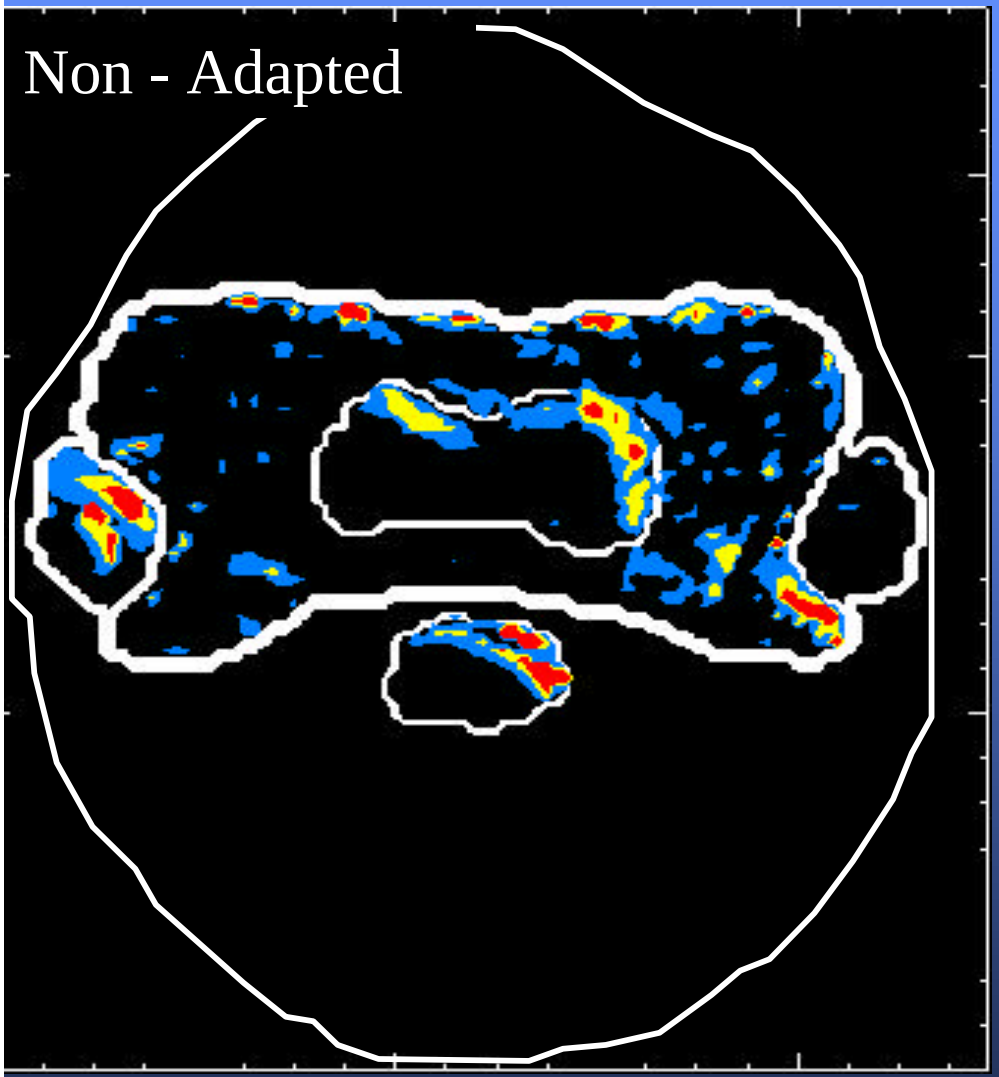
0 to 3 mm(%)	3 to 6 mm(%)
6 to 9 mm(%)	9 to 12 mm(%)

Adapted Dose Distributio



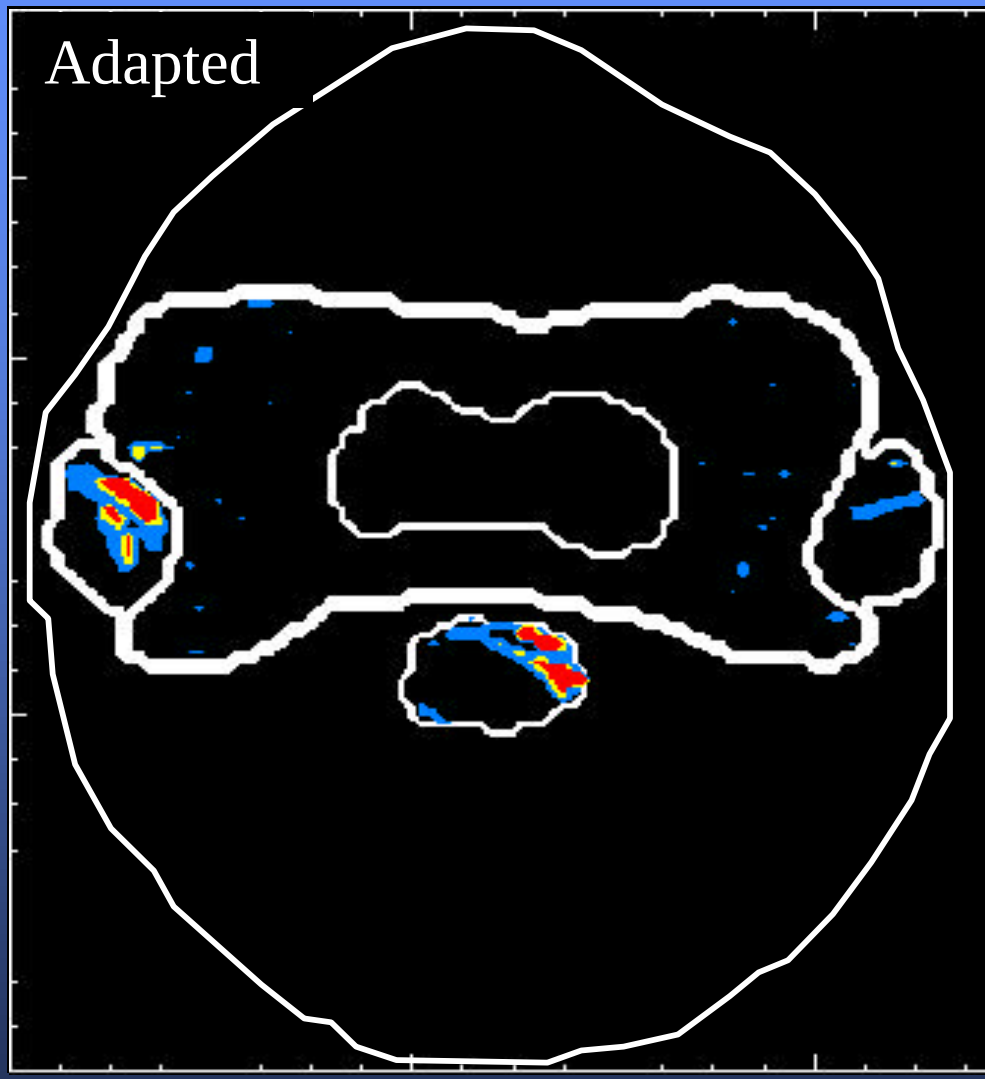
Dose to deliver to correct regret.

Incorrect +Perfect



0 to 3 mm(%)	3 to 6 mm(%)
6 to 9 mm(%)	9 to 12 mm(%)

Incorrect +Corrected



0 to 3 mm(%)	3 to 6 mm(%)
6 to 9 mm(%)	9 to 12 mm(%)

Clinical Implications

- More complex target volumes can be delivered and still spare critical volumes.
- Complex prescriptions or “dose painting”.
- Higher dose/fraction can be delivered to the tumor and still have low dose and dose/fraction to critical tissues.
- Conformal avoidance.
- More accurate setup of the patient.
- Better verification that delivery is correct.
- Have a basis to repair dose distributions.
- Adaptive radiotherapy.

Other Innovative Treatments Tomotherapy Will Enable

- Stereotactic radiotherapy (and radiosurgery) to the body.
- Irradiate entire nodal chains with conformal avoidance.
- Repairing the dose distributions from other modalities, e.g., poor seed implants.
- Combined brachytherapy and IMRT.
- Bone marrow ablation while sparing visceral organs.
- Whole-skin irradiation using IMRT.
- Probability-based prophylactic radiotherapy.
- Swiss-cheese-like dose distributions in normal tissue (3-D grid therapy).
- Great change in breast radiotherapy.

Increased Throughput Possible

- Integration of planning, delivery and verification.
- Potentially easier to commission and calibrate.
- Dose reconstruction eliminates need for on-going patient-specific dosimetry measurements.
- Fewer planning decisions and optimization may be automated.
- High dose rate (8 Gy/min).
- Higher dose/fraction more feasible because normal tissue can be more easily avoided.
- Easier patient setup.
- No couch rotation reducing possibility of collision.
- Tomographic verification images are more easy to interpret than planar portal images.
- Impact of delivery errors can be reduced.
- Increased primary collimation so less staff irradiation per patient.

Conclusions

- Helical tomotherapy is the marriage of a linac with a CT scanner.
- Helical tomotherapy can deliver highly conformal dose distributions.
- Megavoltage CT is sufficient for verification of the setup.
- Dose reconstruction and deformable registration determines the dose actually delivered.
- Adaptive radiotherapy ensures that the whole course of therapy is delivered correctly.
- Tomotherapy provides image-guidance for the whole chain of radiotherapy processes.