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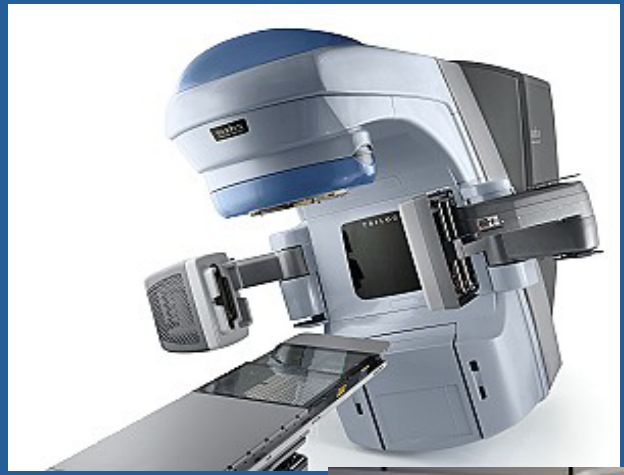
Department of Radiation Oncology

Planning Methods for Rotational IMRT on Linear Accelerators



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Virginia Beach, VA

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Acknowledgements

- Grace Tang
- Dave Shepard
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- Daliang Cao
- Kristen Asbury
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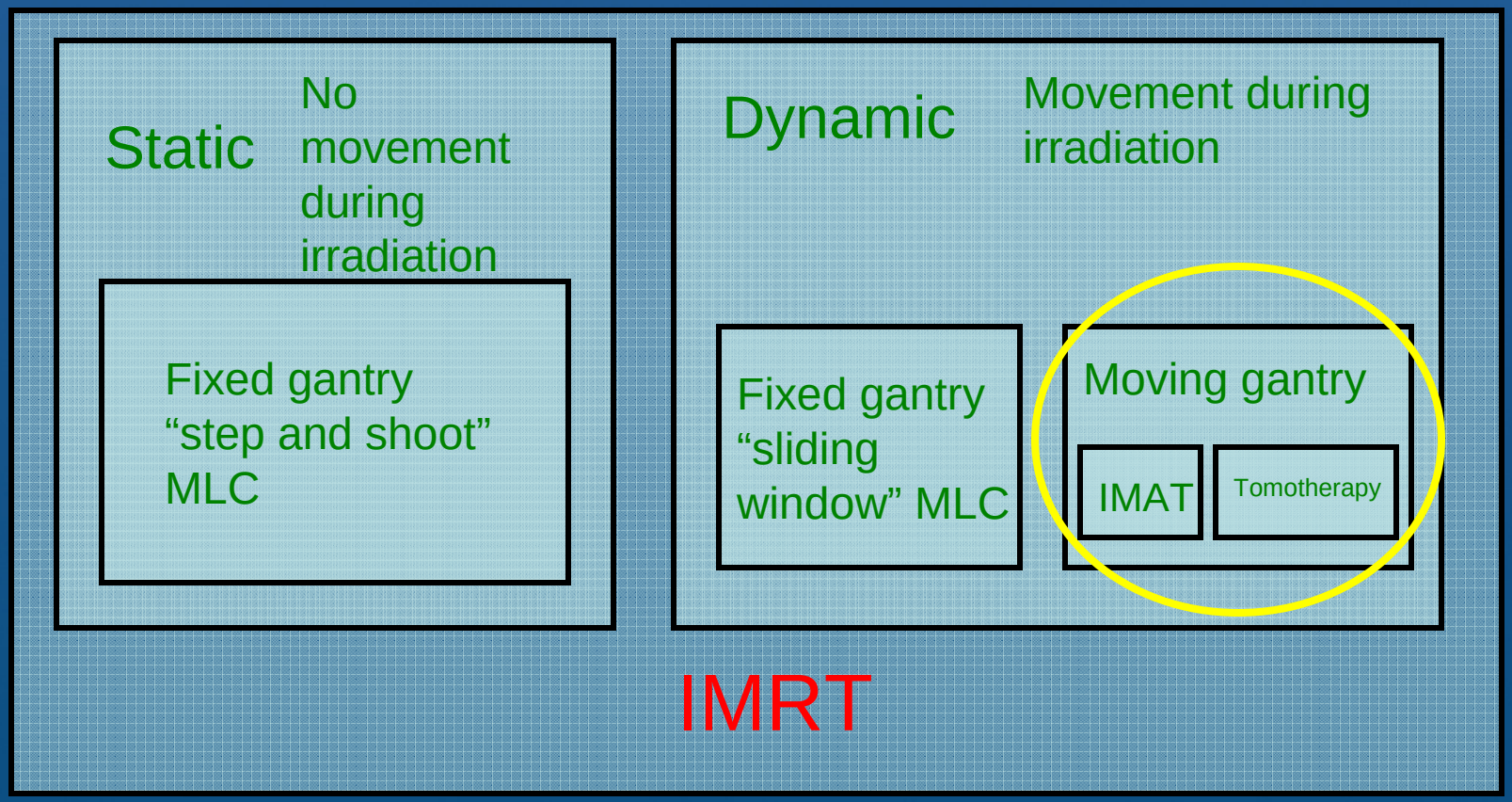
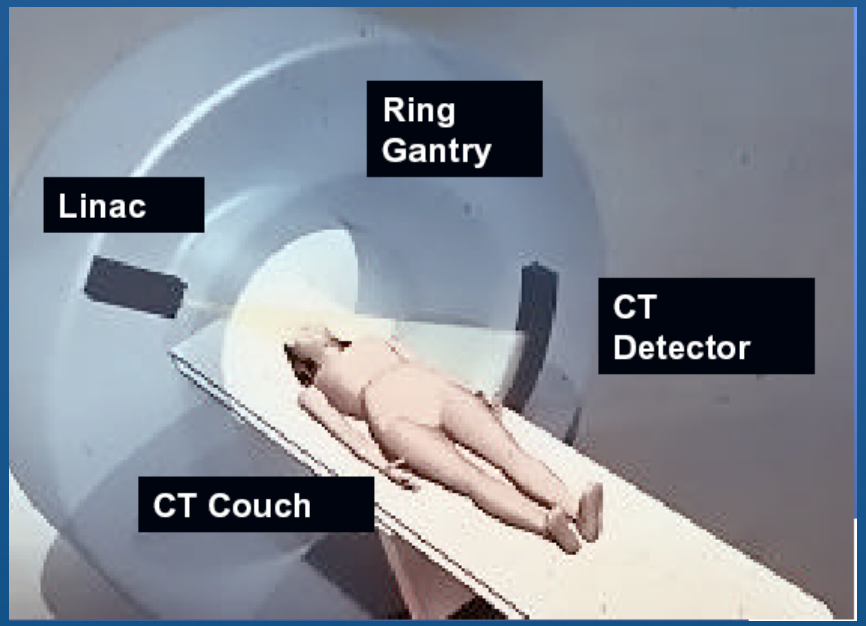
IMRT


Static
No movement during irradiation
Fixed gantry "step and shoot" MLC
Dynamic
Movement during irradiation
Fixed gantry "sliding window" MLC
Moving gantry
IMAT
Tomotherapy
IMRT

Rotational IMRT



Tomotherapy

1) Target irradiated “slice-by-slice”
2) Dedicated unit required

Linac Based

1) Target irradiated “volumetrically”
2) Can be performed on a “conventional” linac

Linac Based Rotational IMRT

1) Radiation continuously delivered while the gantry rotates around patient.
2) MLC changes shape during gantry rotation
3) IMAT: Multiple overlapping “arcs” produce intensity modulation from any given gantry angle
4) VMAT/AMRT: Single arc

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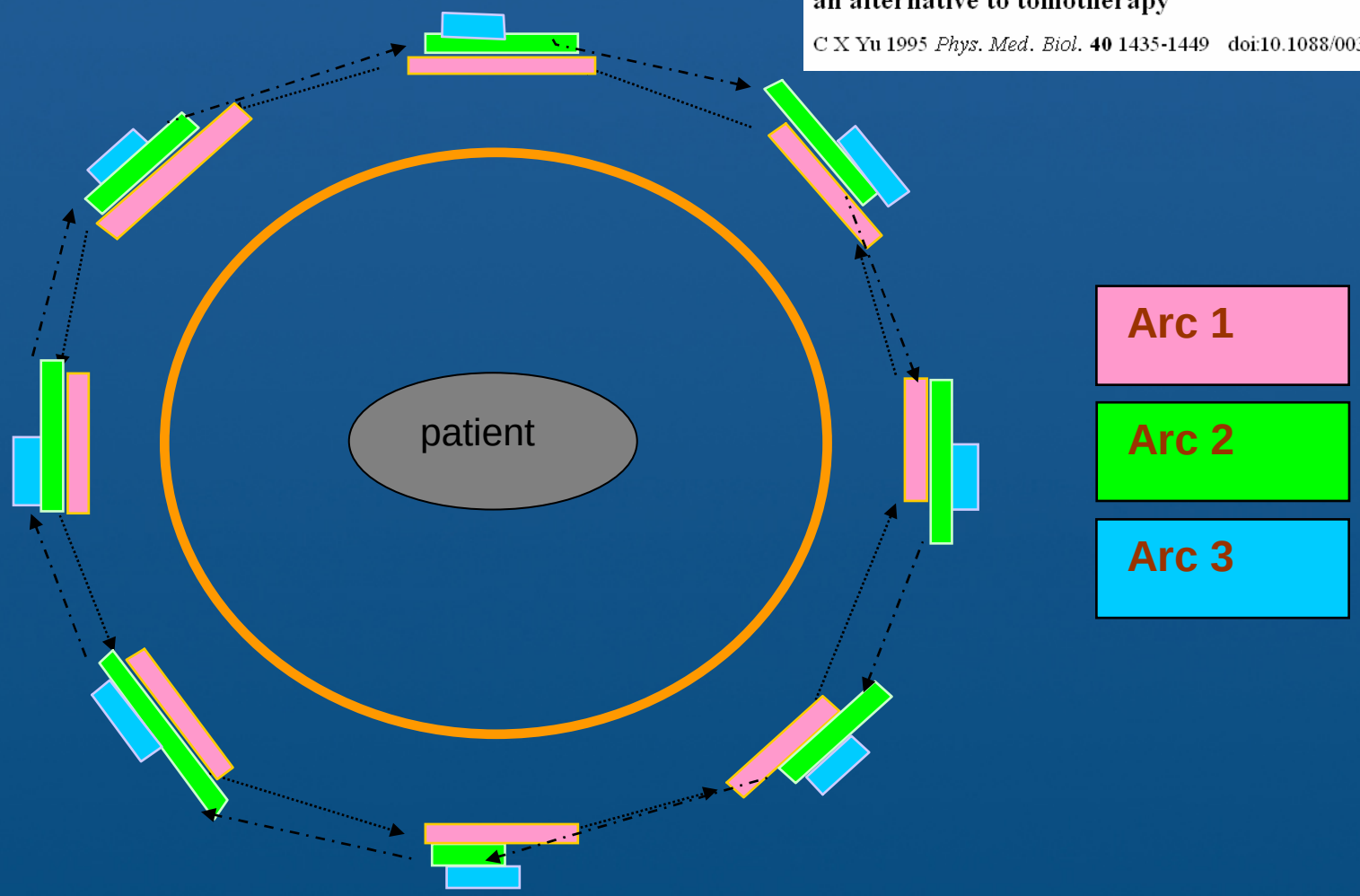
Intensity-Modulated Arc Therapy (IMAT)

Intensity-modulated arc therapy with dynamic multileaf collimation: an alternative to tomotherapy

C X Yu 1995 *Phys. Med. Biol.* **40** 1435-1449 doi:10.1088/0031-9155/40/9/004



Multiple rotations of the gantry around patient produce intensity modulation from any given beam direction

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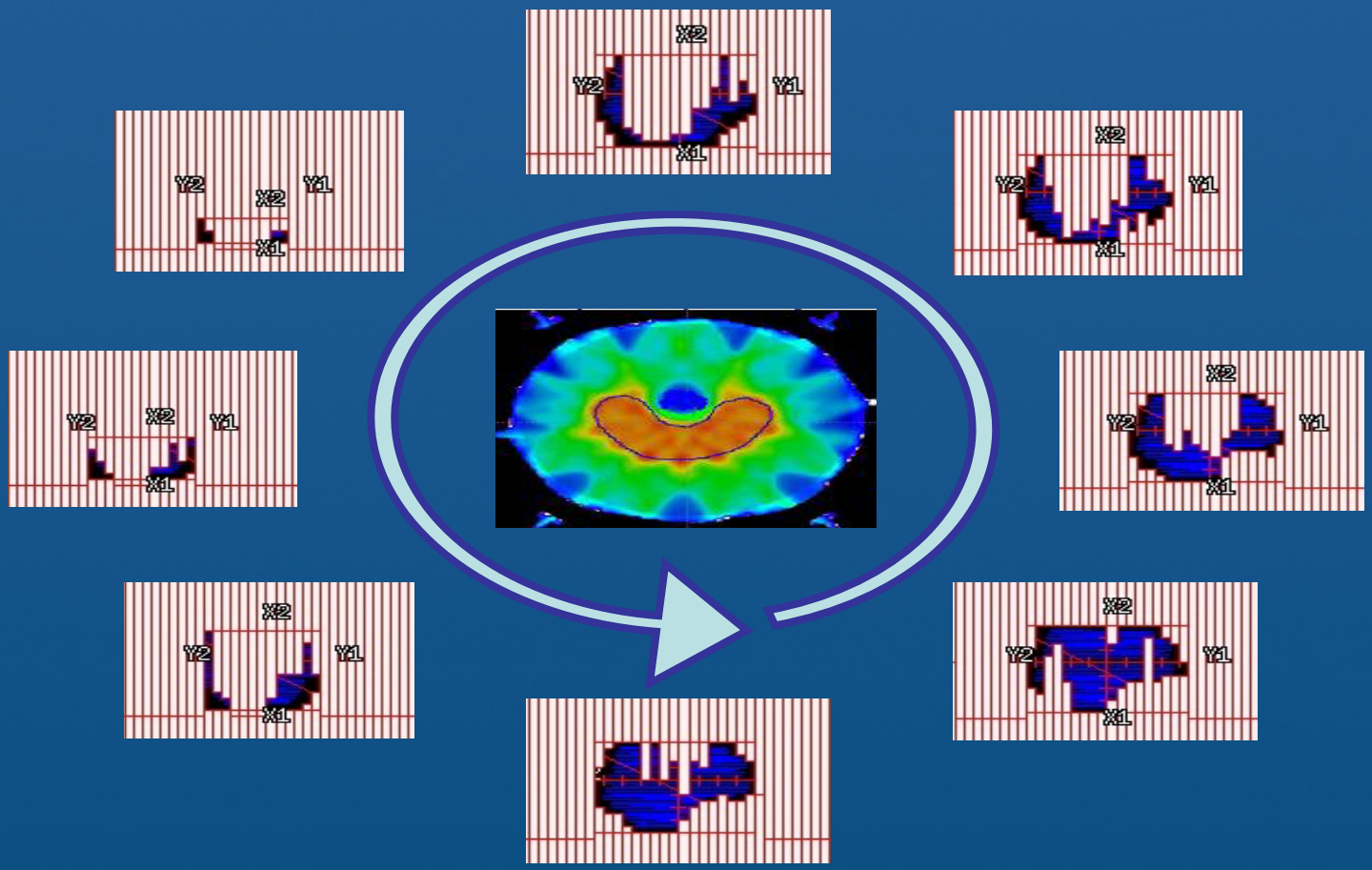
Single arc delivery



Single rotation of the gantry around patient produce intensity modulation in the volume: VMAT (Volumetric modulated arc therapy) and AMRT (Arc modulated radiation therapy)

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Why rotational IMRT?

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

The bottom line is that you can get a better plan with more beams

Shepard et al, "A simple model for examining issues in radiotherapy optimization," Medical Physics **26**(7), 1212-21 (1999).

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Why not rotational IMRT?

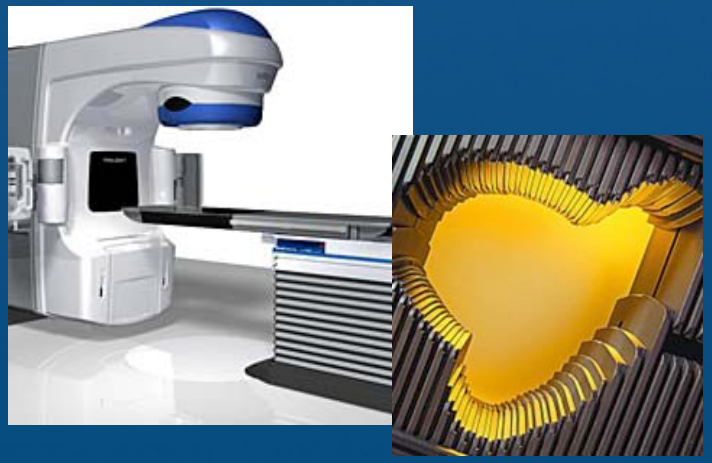
Due to the complexity of rotational IMRT planning and delivery, its benefits have until recently gone largely unrealized

Planning:

1) Computationally Intensive
2) Take into account delivery constraints
3) Lack of robust algorithms

Delivery:

1) Dose rate modulation
2) Gantry speed modulation
3) Leaf movement during rotation



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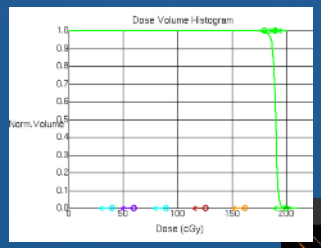
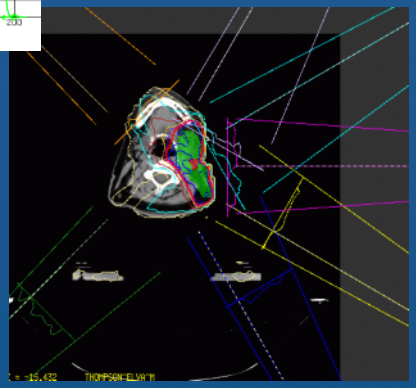
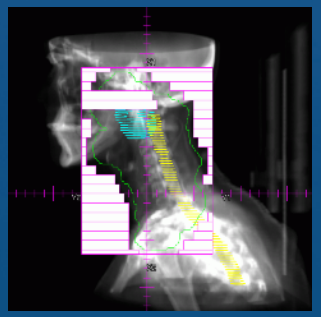
Planning Process







Contouring:
Target, normal structure delineation

Define treatment objectives

Arc range selection?

Optimization

Aperture based optimization

Fluence based optimization

Leaf sequencing
(omit for aperture based optimization)

Final Dose Calculation

Final Evaluation

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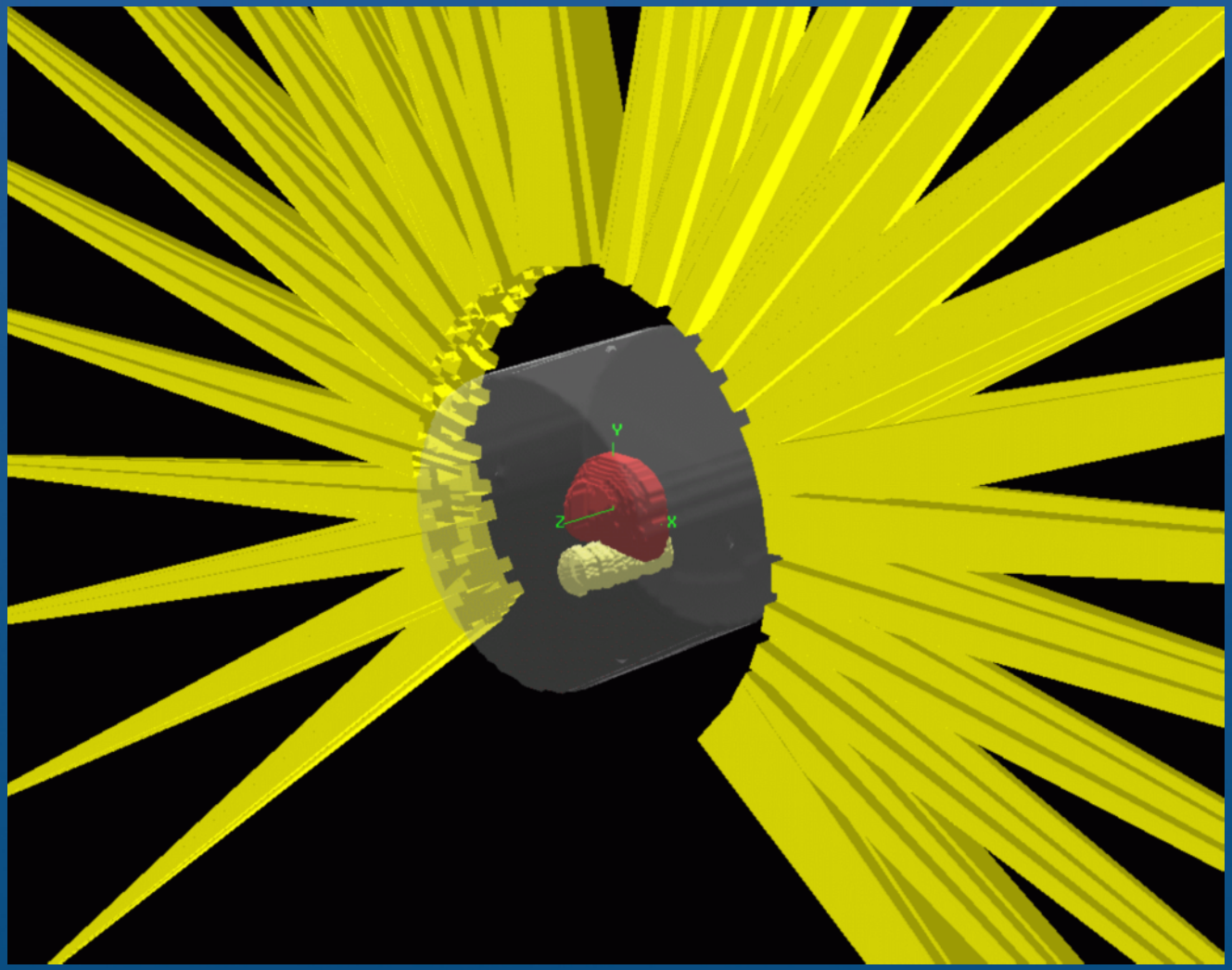
Beam angle “selection”



To start, a continuous arc is approximated by a series of static beams

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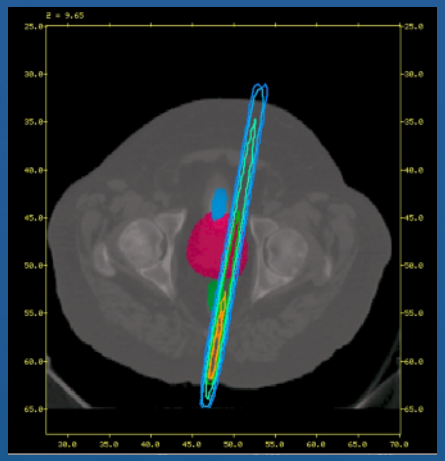
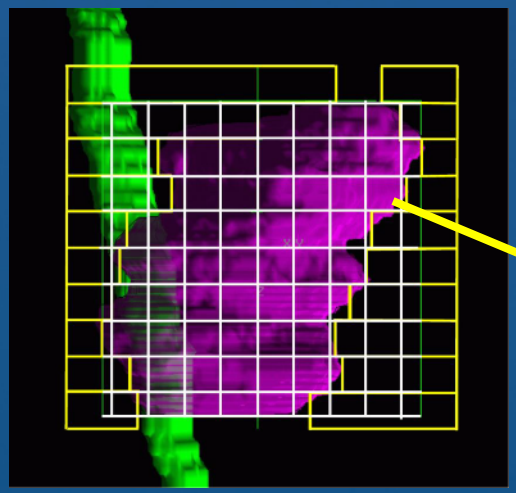
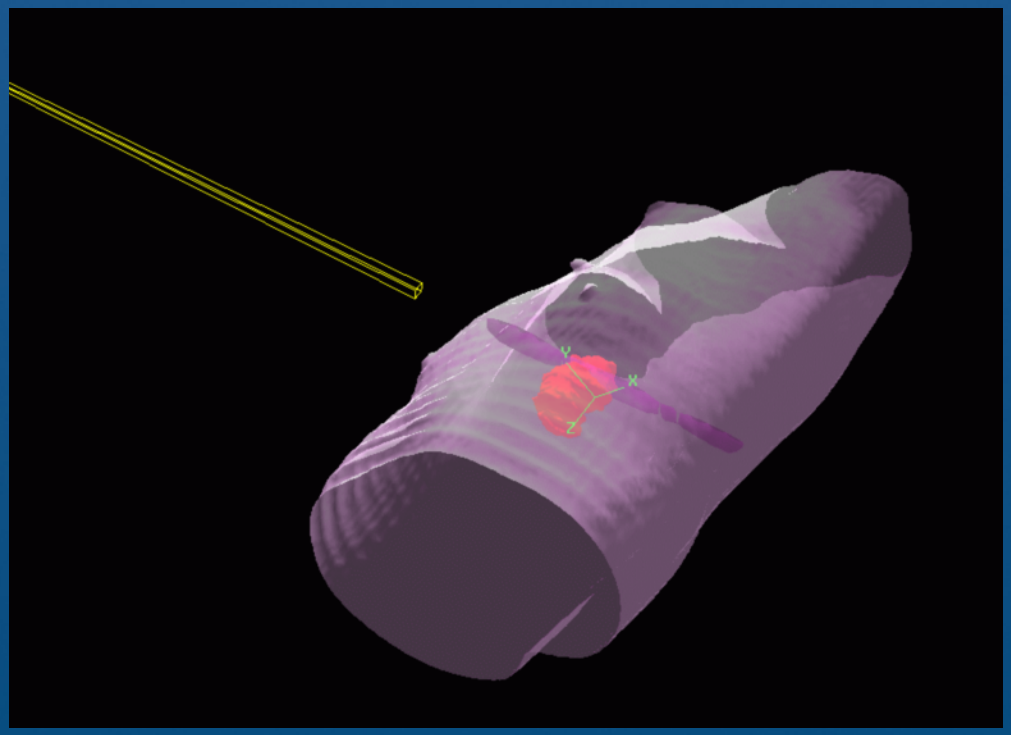
Pencil Beams



Divide the field into "pencil beams" and compute dose distributions for all pencils.





First problem: Computer memory resource requirements.

For example 10x10 with 0.25cm^2 PB resolution and 100k pencils is about 1.5GB

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Two techniques

Two-step process:

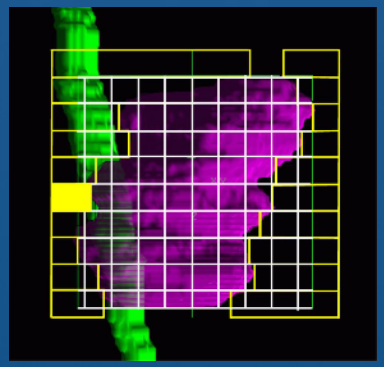
1) Optimize the relative weightings of the pencil beams to meet clinical objectives
2) Delivery constraints ignored during optimization
3) A separate “leaf-sequencing” step is required to transform optimal fluence maps into deliverable aperture shapes

Aperture-Based:

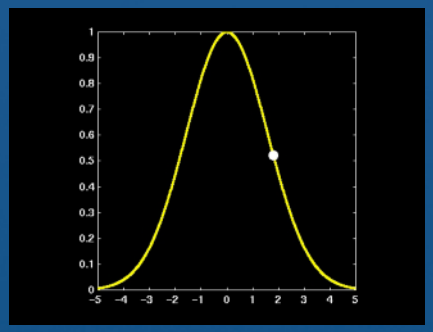
1) Optimize the leaf positions and relative weightings of the apertures
2) Delivery constraints are taken into account during the optimization
3) “Leaf-sequencing” not required
4) For example, Direct Aperture Optimization (DAO) and Direct Machine Parameter Optimization (DMPO)

DAO Methodology

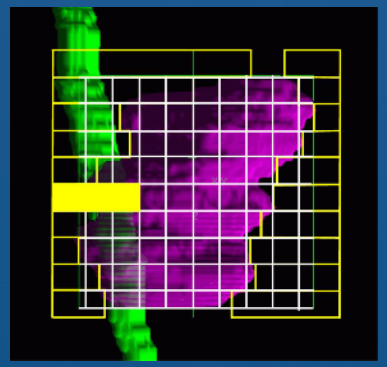
Pick a parameter:
(eg. 5th leaf of 4th angle in 2nd aperture)



Sample size of change from a Gaussian distribution



Make the change



Does change satisfy delivery contraints?

No

Yes

Calculate new dose and Objective function value (can be Dose, DVH, or Biological)

$$O = \frac{1}{N}\sum_{i=1}^{N} w_i \left(d_i - d_{i,p}\right)^2$$

Simulated Annealing

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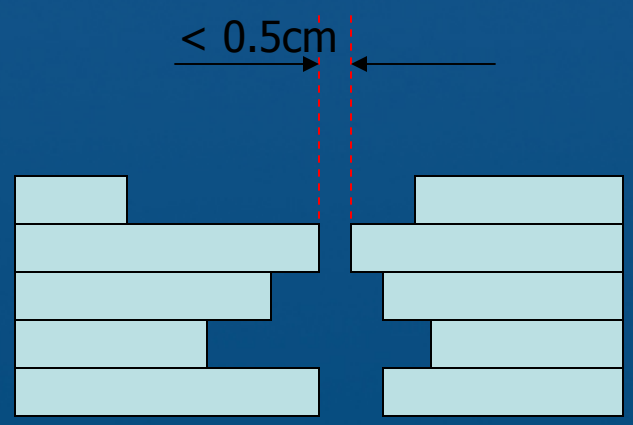
MLC Constraints

Every multi-leaf collimator has delivery constraints:

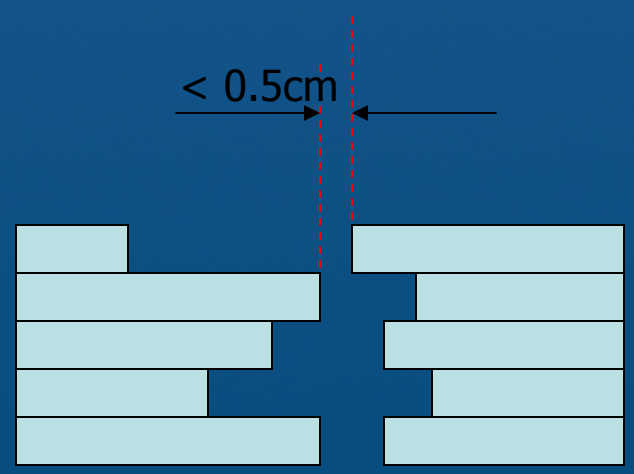
Some sample Elekta constraints:

1) Opposed leaves cannot come within 0.5-cm of one-another



Not allowed

2) Opposed-adjacent leaves cannot come within 0.5-cm of one-another



Not allowed

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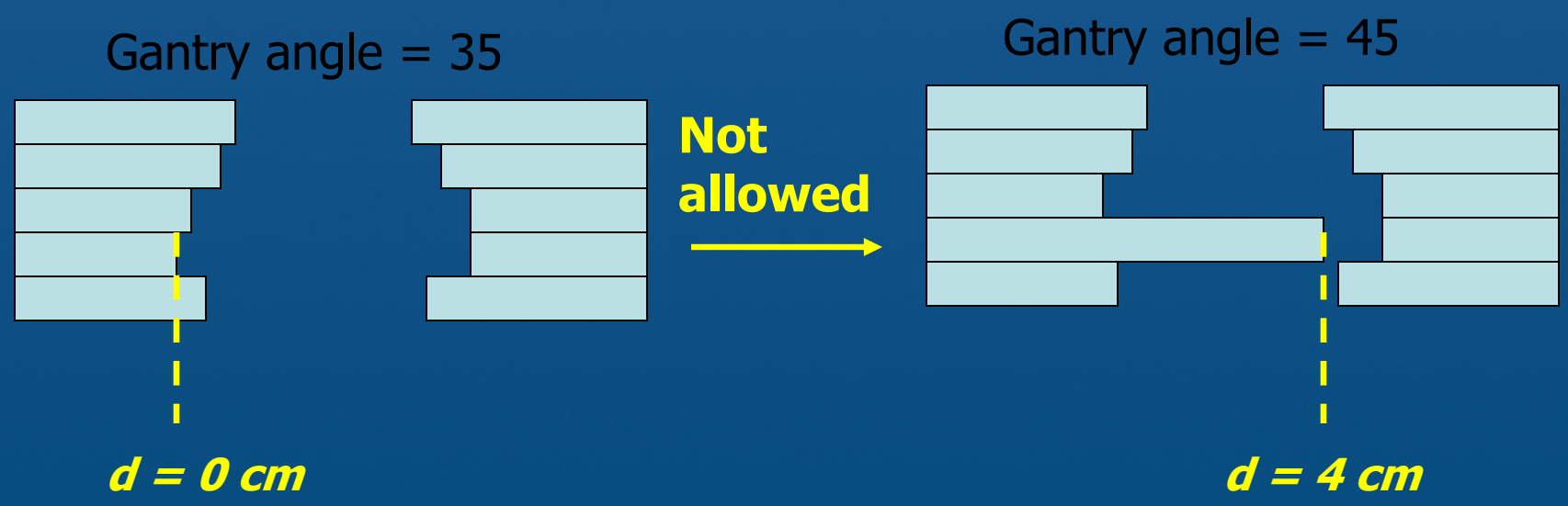
Rotational Constraints: Delivery

In addition to the contraints imposed by the static MLC, there are also constraints imposed by the leaf movement

Leaf movement constrained by:

a) Maximum leaf travel speed
b) Gantry speed

e.g. If gantry speed is 10 degrees/sec and leaf travel speed is 2 cm/sec, maximum leaf travel between two adjacent angles is 2-cm



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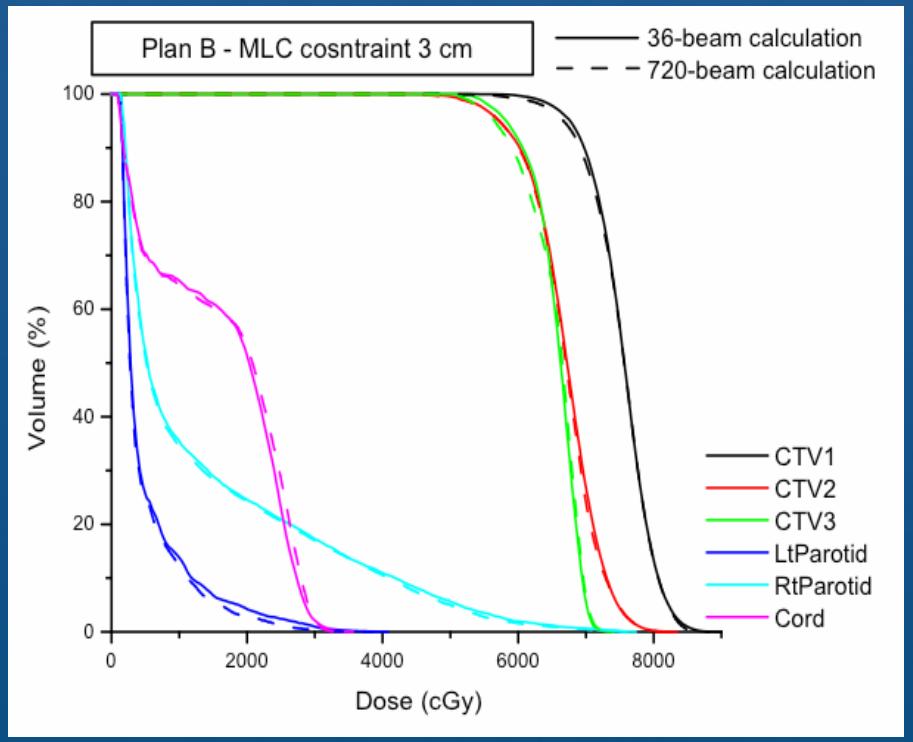
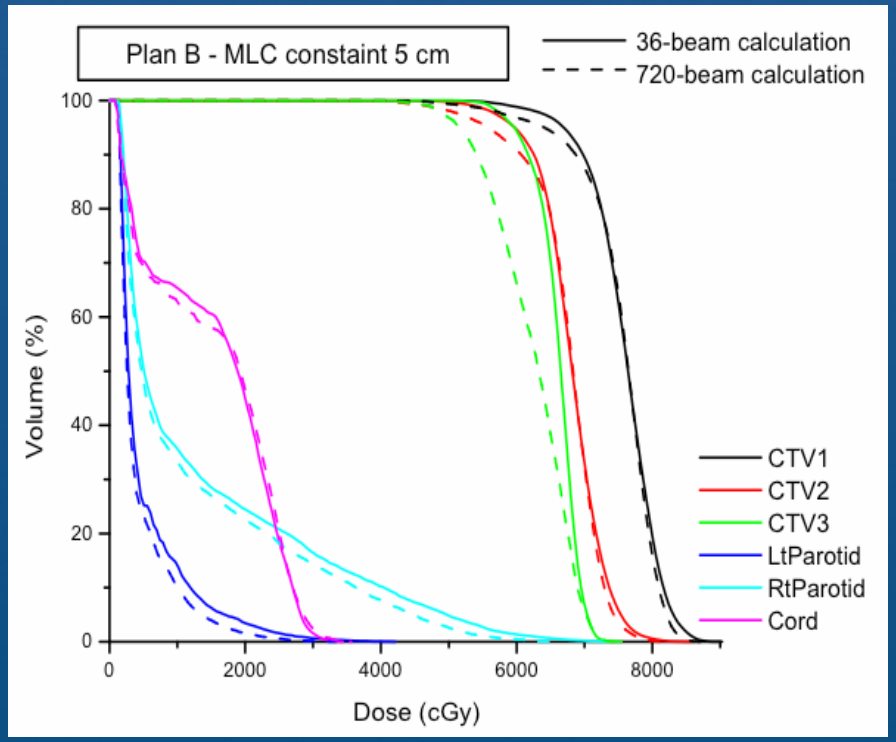
Rotational Constraints: Dosimetric

1) Dosimetric considerations as well
2) Inaccuracies in dose delivery due to large leaf changes between adjacent angles



Allow 3cm leaf travel



Allow 5cm leaf travel

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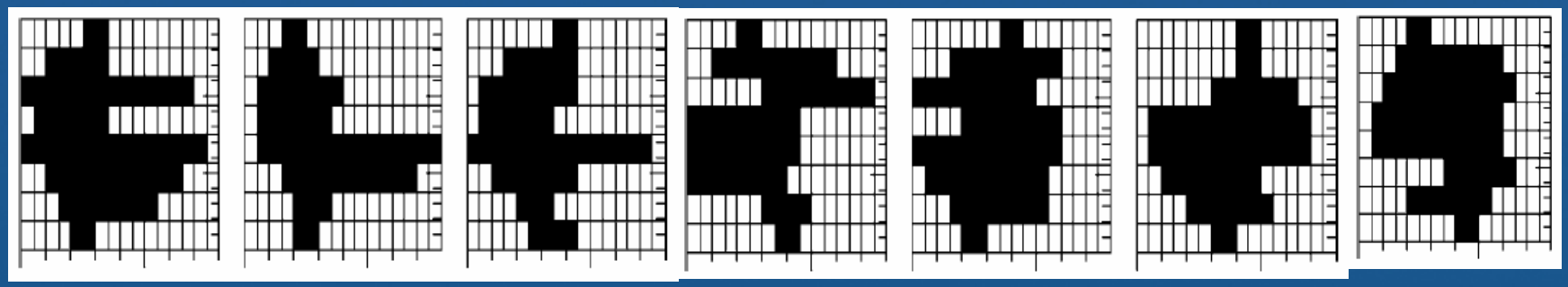
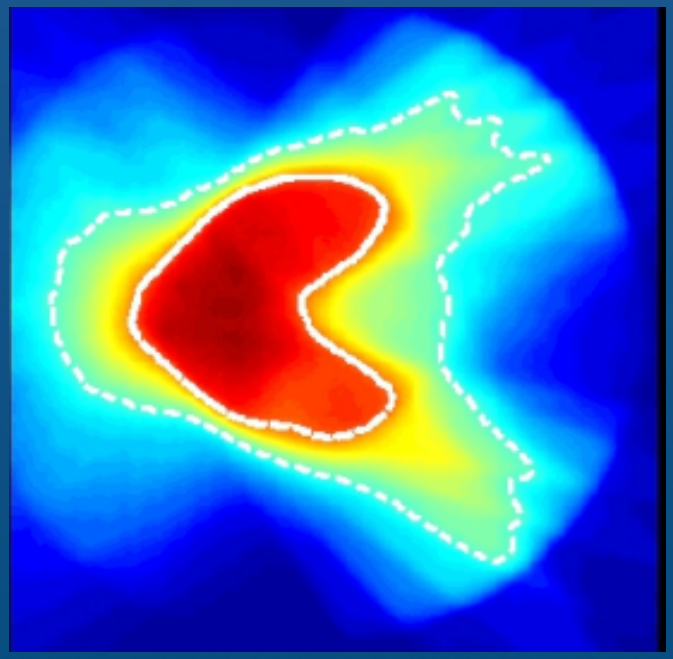
Courtesy Grace Tang

Dose Rate Based Constraints

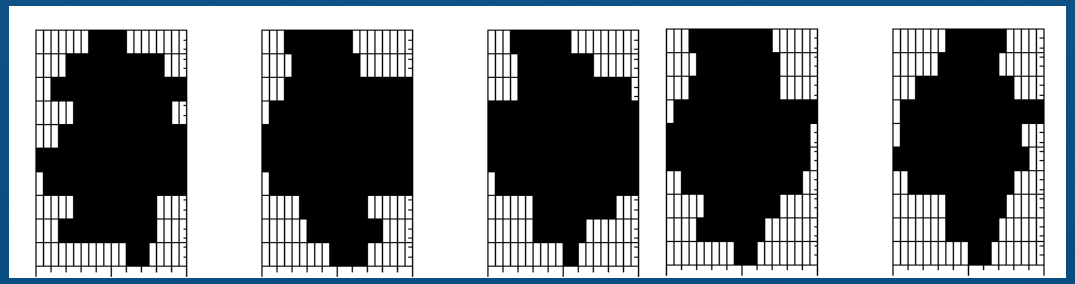
1) Constant dose rate: apertures within arc have same weight
2) Variable dose rate: apertures within arc have different weighting
3) Variable dose rate allows more freedom… better plans
4) Linear accelerator manufacturers have recently implemented VDR control systems

DAO Applied to multi-rotation IMAT





In general, worked reasonably well, however apertures often did not deviate much from their starting point (beam's eye view)



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DAO Applied to multi-rotation IMAT

Any other ideas??

1) Revisit sequencing?
2) Different starting point for optimization?

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Two-step approach

The two steps are:

1) Optimization of fluence maps for each beam direction - delivery constraints not taken into account

2) Convert the fluence maps into deliverable MLC shapes conforming to previously mentioned delivery constraints

Beamlet weight optimization

Look for the minimum of this function (for example)

$$O = \frac{1}{N}\sum_{i=1}^{N} w_i \left(d_i - d_{i,p}\right)^2$$

By altering the pencil beam weightings $\boldsymbol{a_j}$

$$d_i^d = \sum_{j=1}^{n_{PB}} D_{ij} a_j$$

We'll figure out how to deliver it later… with our sequencer

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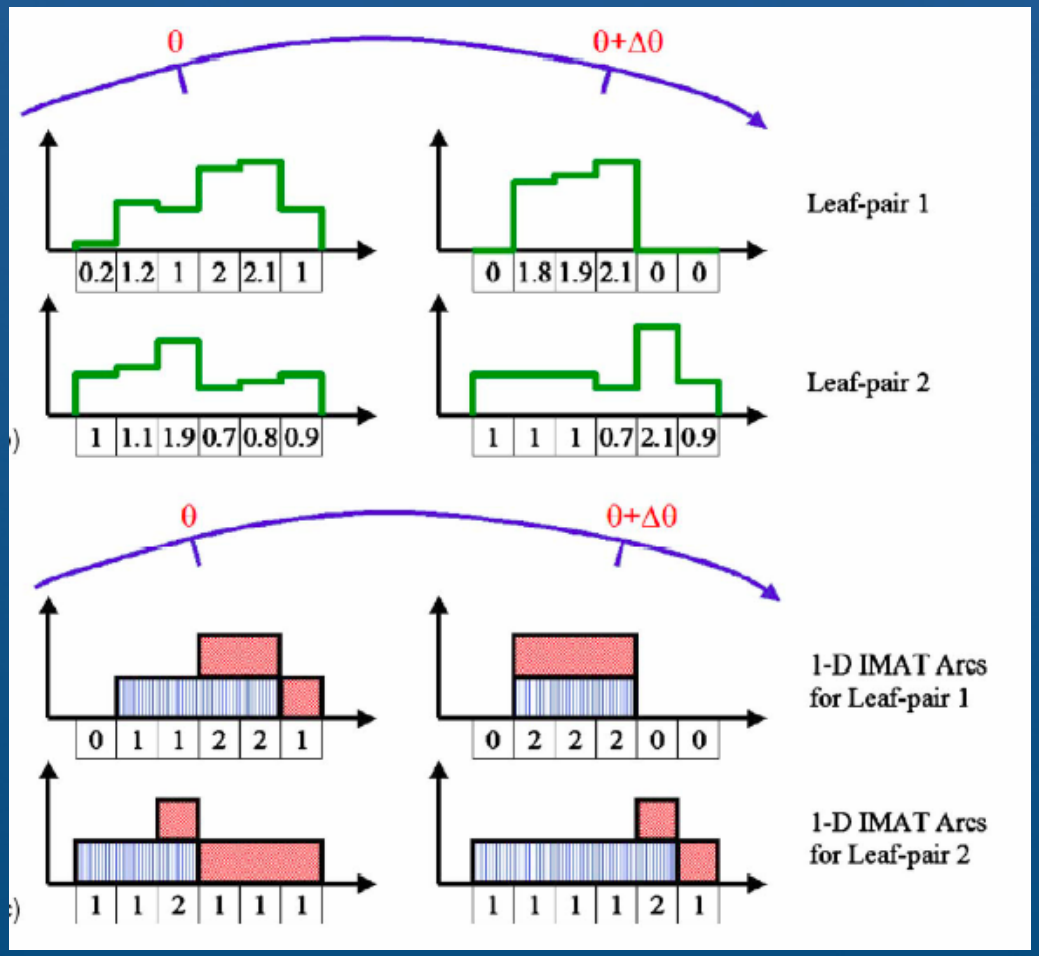
Sequencer: *"klink"*

Luan, S. Et al, "Leaf-sequencing for intensity modulated arc therapy using graph algorithms," Medical Physics **35**(1), 61-67 (2008).



1) Simplify intensity map
2) Find *k* leaf openings to deliver simplified intensity map with minimal error from optimal map
3) Adjust openings to conform to maximum leaf motion constraint
4) Do a segment weight optimization to minimize error

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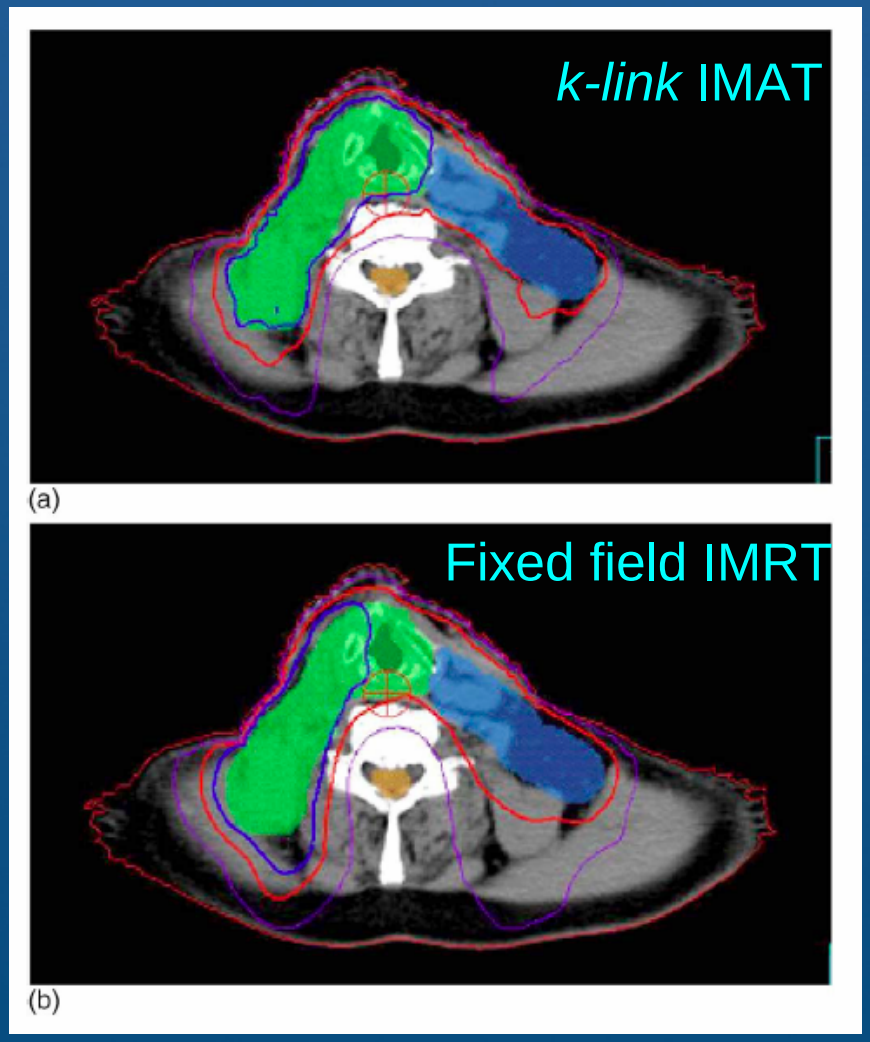
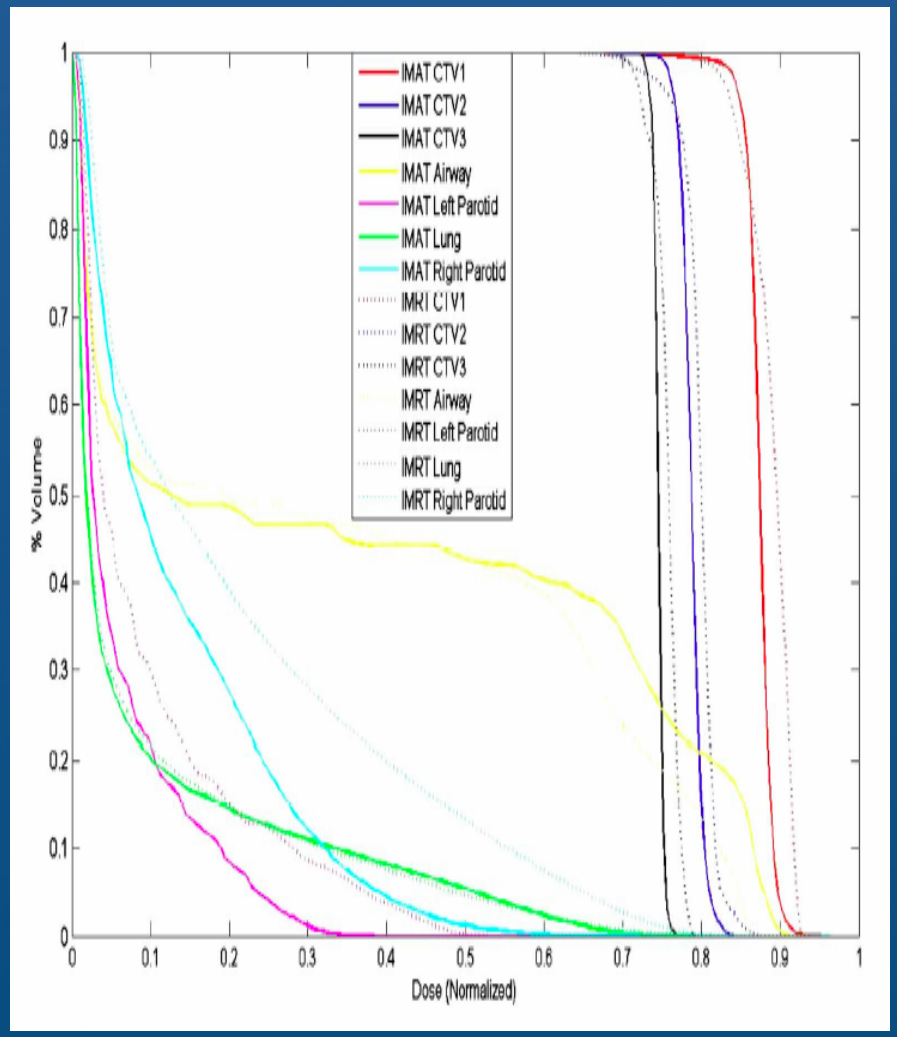
Sample *"klink"* Result

Luan, S. Et al, "Leaf-sequencing for intensity modulated arc therapy using graph algorithms," Medical Physics **35**(1), 61-67 (2008).





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Sequencer: *"CIMO"*

Cao, D. *et al*, "Continuous intensity map optimization (CIMO): A novel approach to leaf sequencing in step and shoot IMRT," Medical Physics **33**(4), 859-867 (2006).

1) CIMO utilizes a technique similar to DAO to sequence an intensity map
   a) Pick a parameter (leaf, aperture weight)
   b) Change it
   c) Does change satisfy delivery constraints?
   d) If so, compute new objective function value
   e) If new objective is better, keep it, if not keep it with a certain probability
2) Instead of a dose based objective function, CIMO utilizes the sum of absolute differences (SOAD) between the optimal and sequenced intensity map

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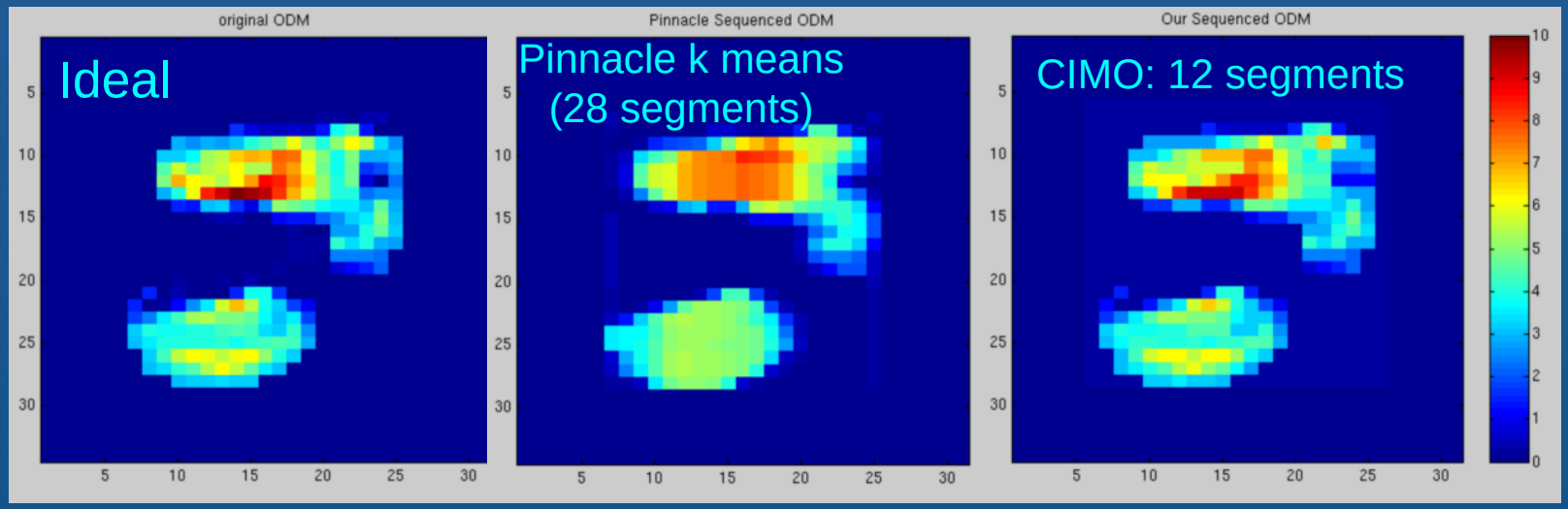
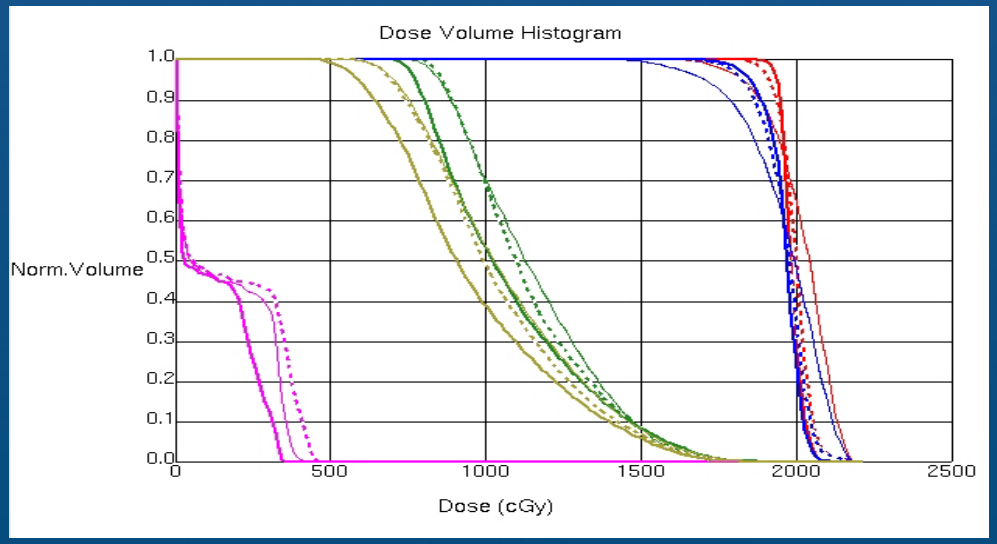
Sample *"CIMO"* Step and shoot Result





Thick solid: ideal
Thin solid: k means
Dashed: CIMO

From Daliang Cao

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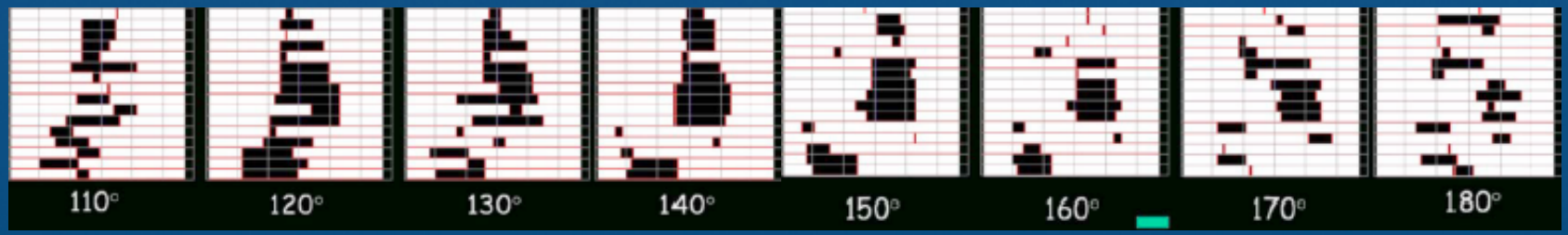
"CIMO" for IMAT

Shepard et al, "An arc-sequencing algorithm for intensity modulated arc therapy," Medical Physics **34**(2), 464-470 (2007).

1) CIMO was first used with step-and-shoot IMRT
2) Like DAO, the ultimate goal for CIMO was a solution for IMAT
3) Simply incorporate the rotational based delivery constraints into the optimization
4) After sequencing, segment weight optimization to improve any degradation from sequencing



Sample arc sequence from CIMO: leaves don't travel more than 3cm

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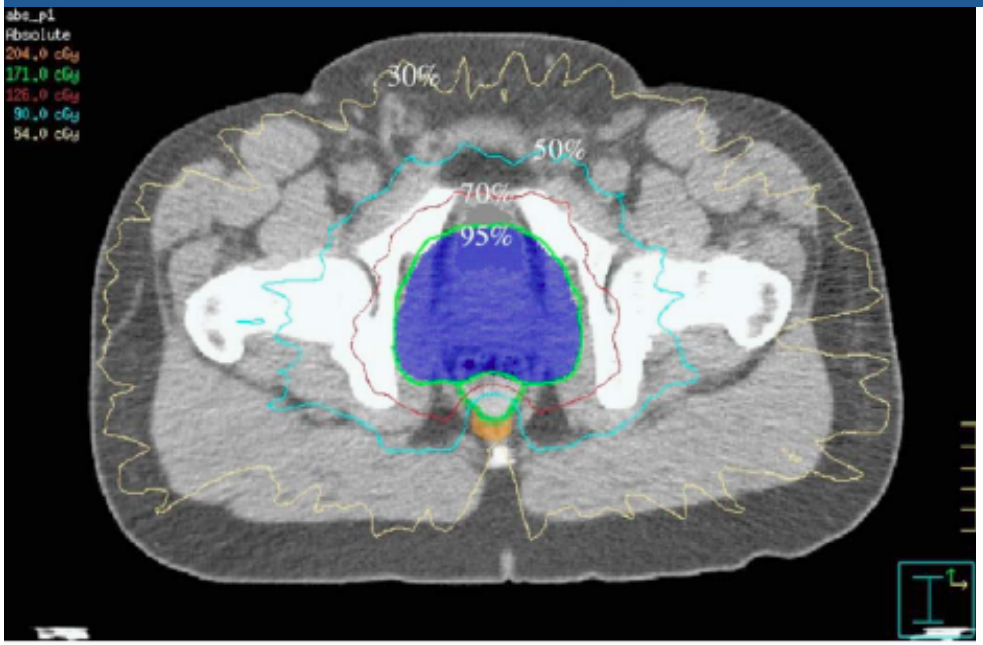
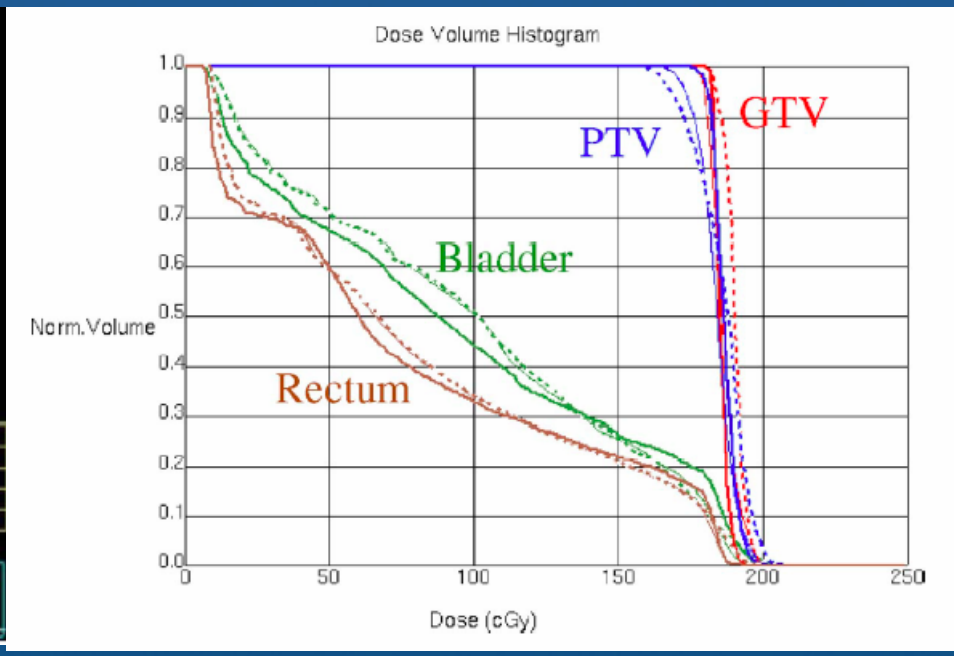
Sample *"CIMO"* IMAT Result





CIMO sequenced plan computed in Pinnacle

Solid: Ideal
Dashed: CIMO sequenced

Courtesy Dave Shepard, Swedish Cancer Institute

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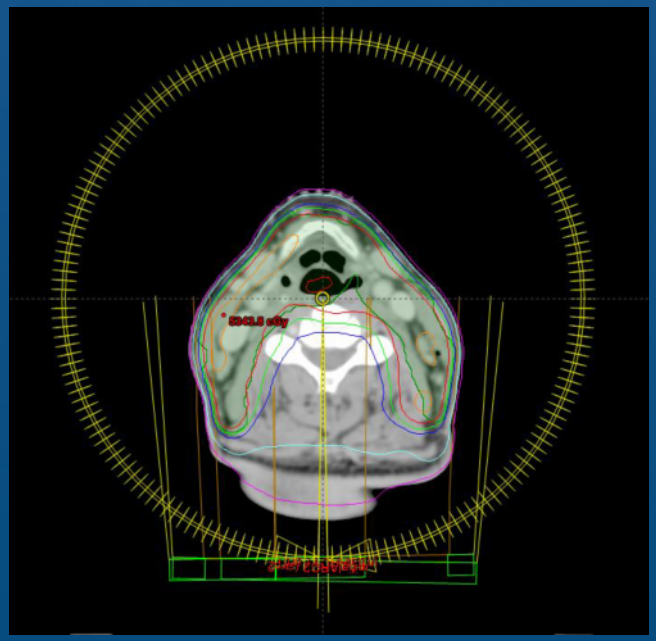
Single Arc Delivery

Increased delivery efficiency has motivated the development of algorithms to deliver rotational IMRT plans in a single rotation of the gantry. The term “Volumetric modulated arc therapy” (VMAT) has been coined to describe this type of delivery

1) RapidArc: aperture based (Varian)
2) Ergo++: anatomy based (Elekta)
3) SmartArc: aperture based (Philips)
4) AMRT: sequence based



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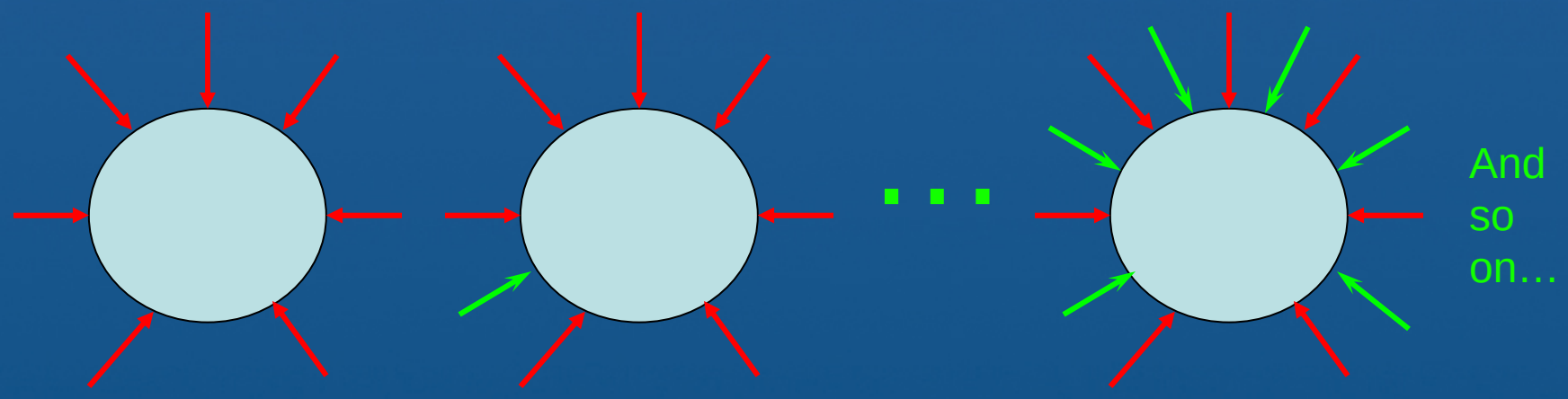
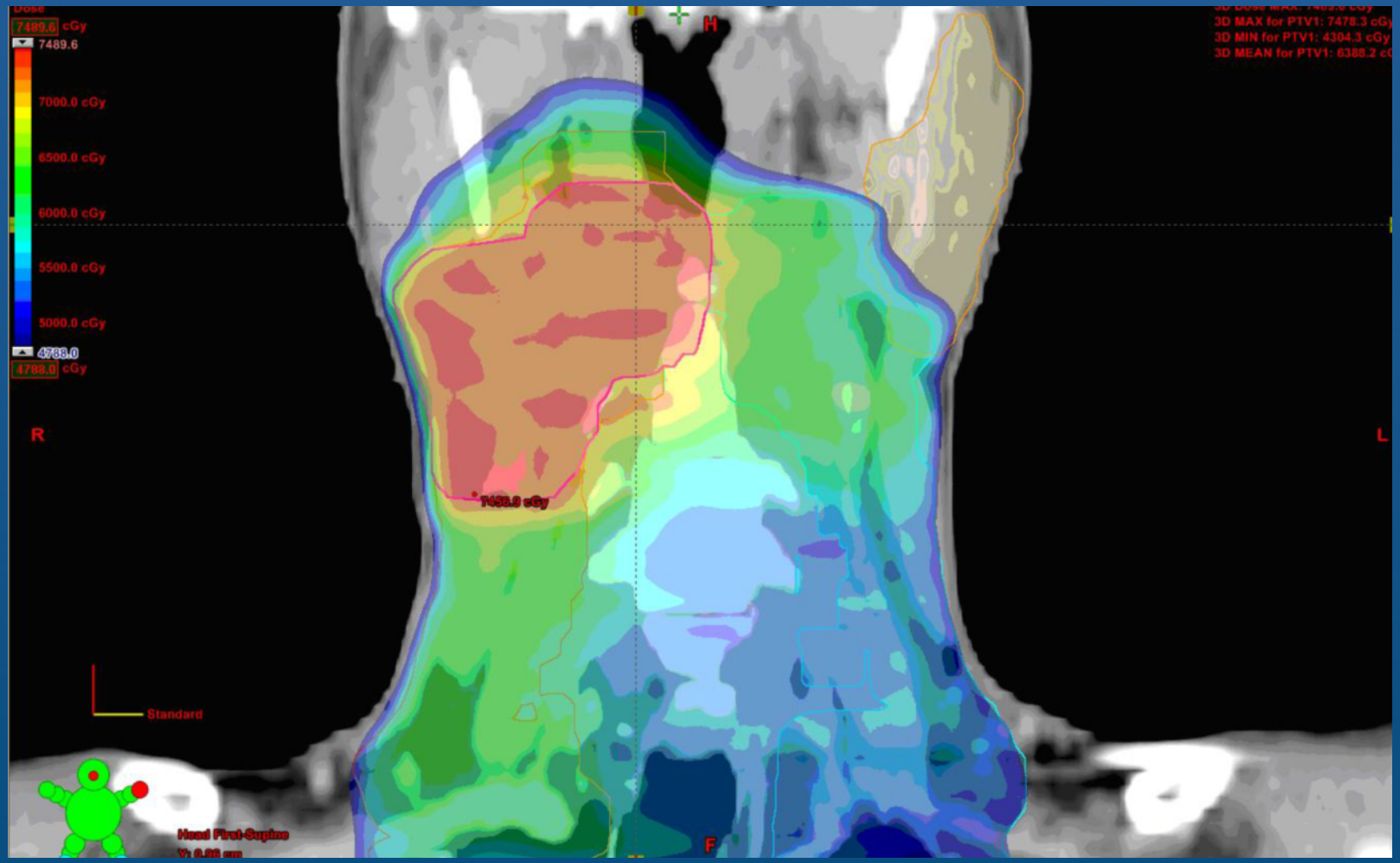
Varian's RapidArc

Otto, K. "Volumetric modulated arc therapy: IMRT in a single gantry arc," Medical Physics 35(1) 310-317 (2008).



1) DAO based optimization
2) Start with "arc" approximated by static beams of coarse spacing
3) Delivery constraints loose at start due to coarse spacing
4) Add more beams as optimization progresses
5) Delivery constraints become more stringent
6) End up with up one arc of 177 control points

RapidArc Example: HN



Initial: 50.4 Gy SFB1: 9 Gy SFB2: 10.8 Gy

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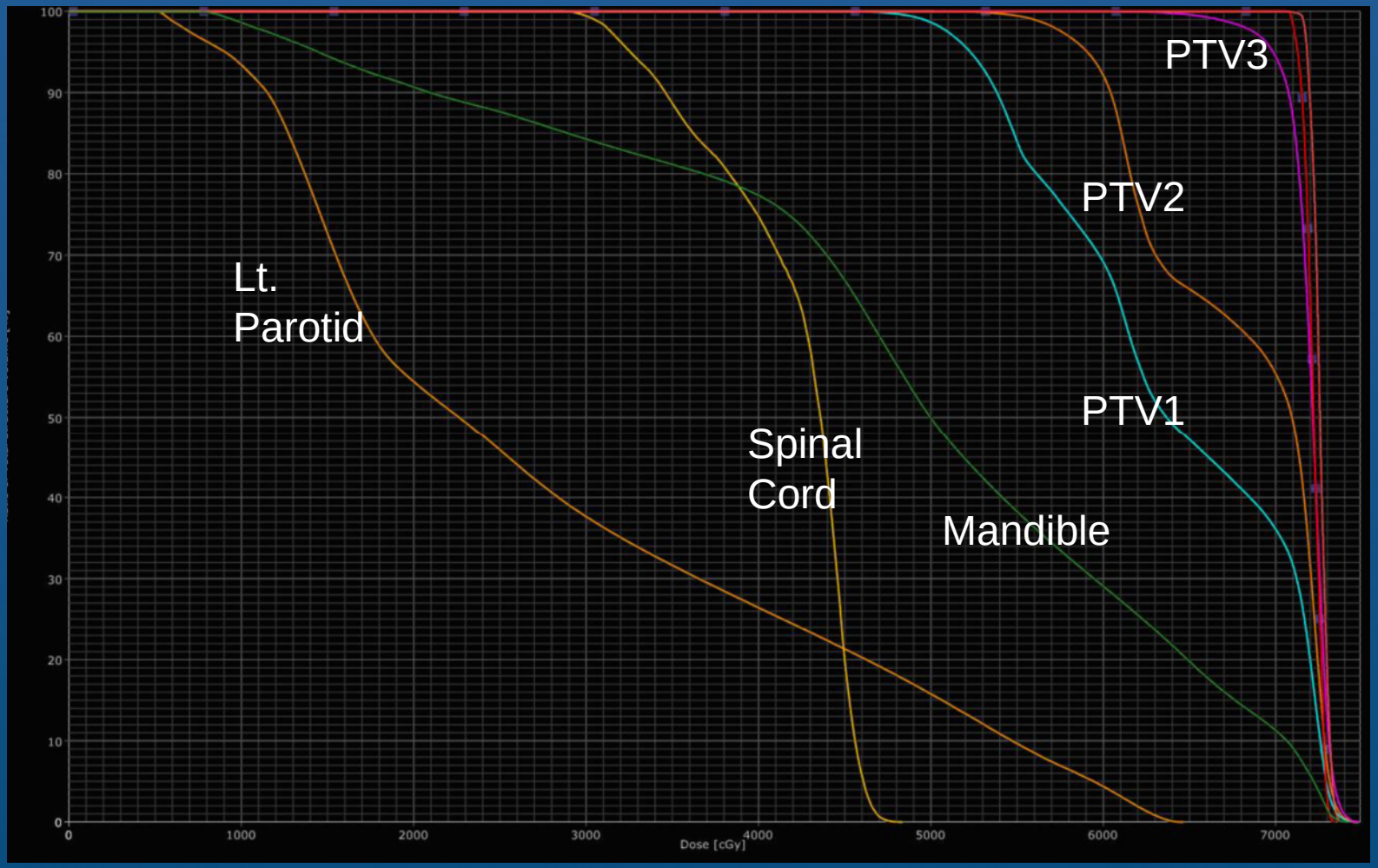
RapidArc Example: HN DVH



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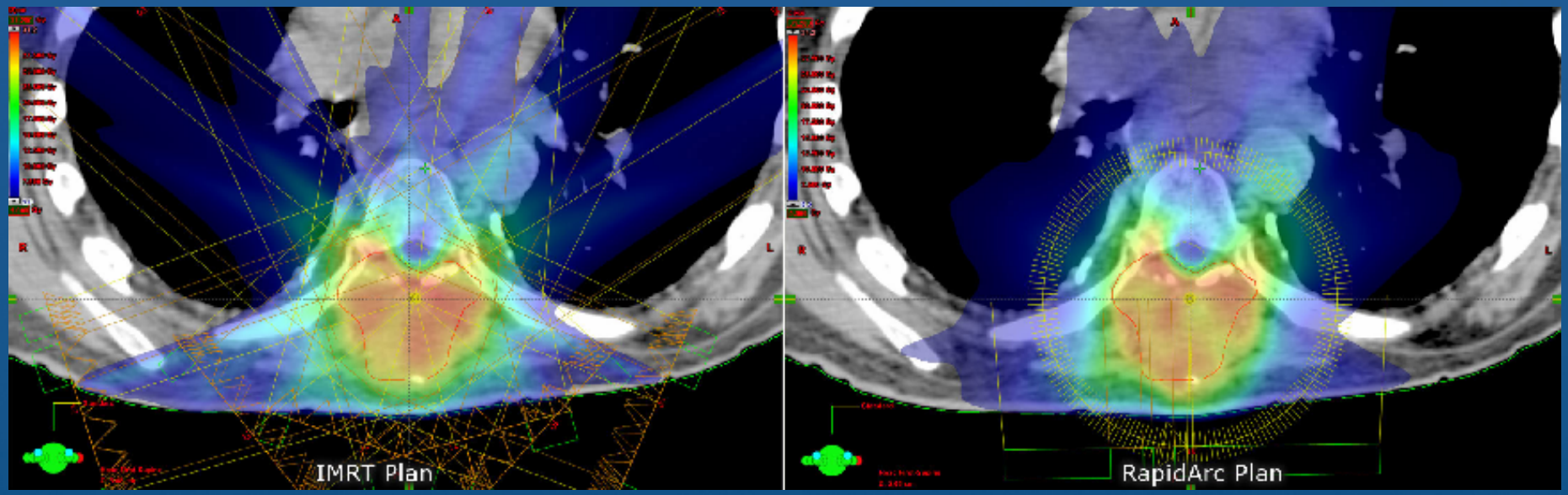
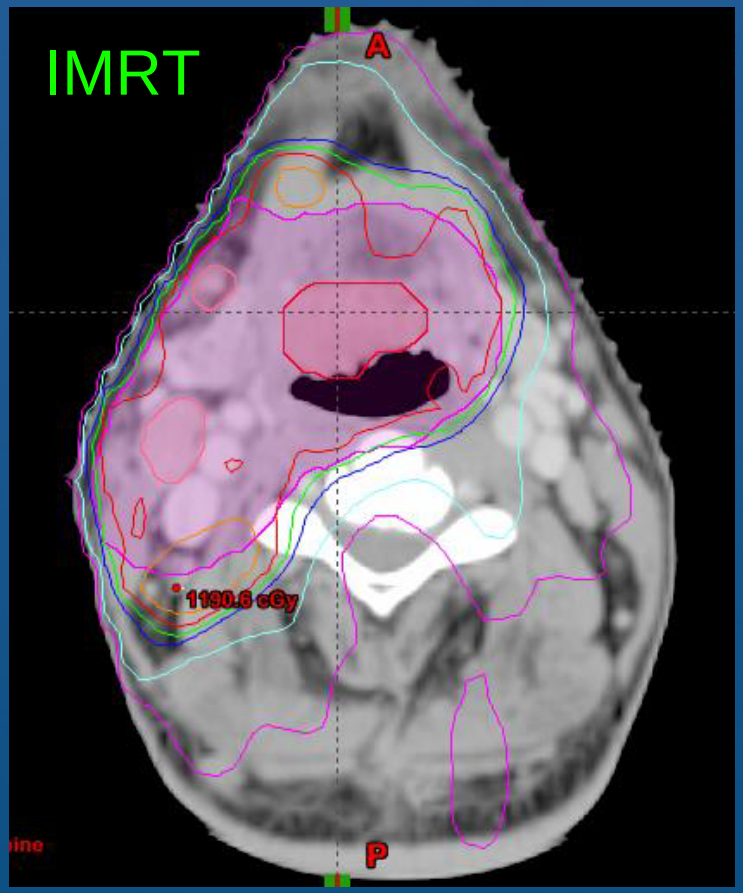
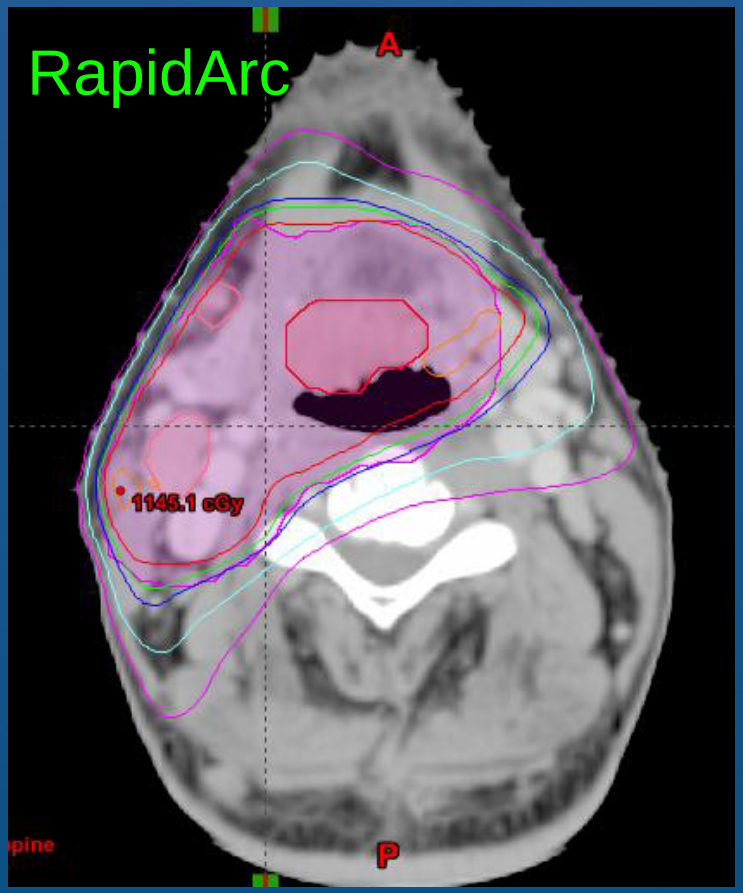
RapidArc Example: Spine



This shows the comparison between a fixed field IMRT plan and a RapidArc plan. Similar dose distributions, but the RapidArc plan can be delivered in 1-2 minutes.

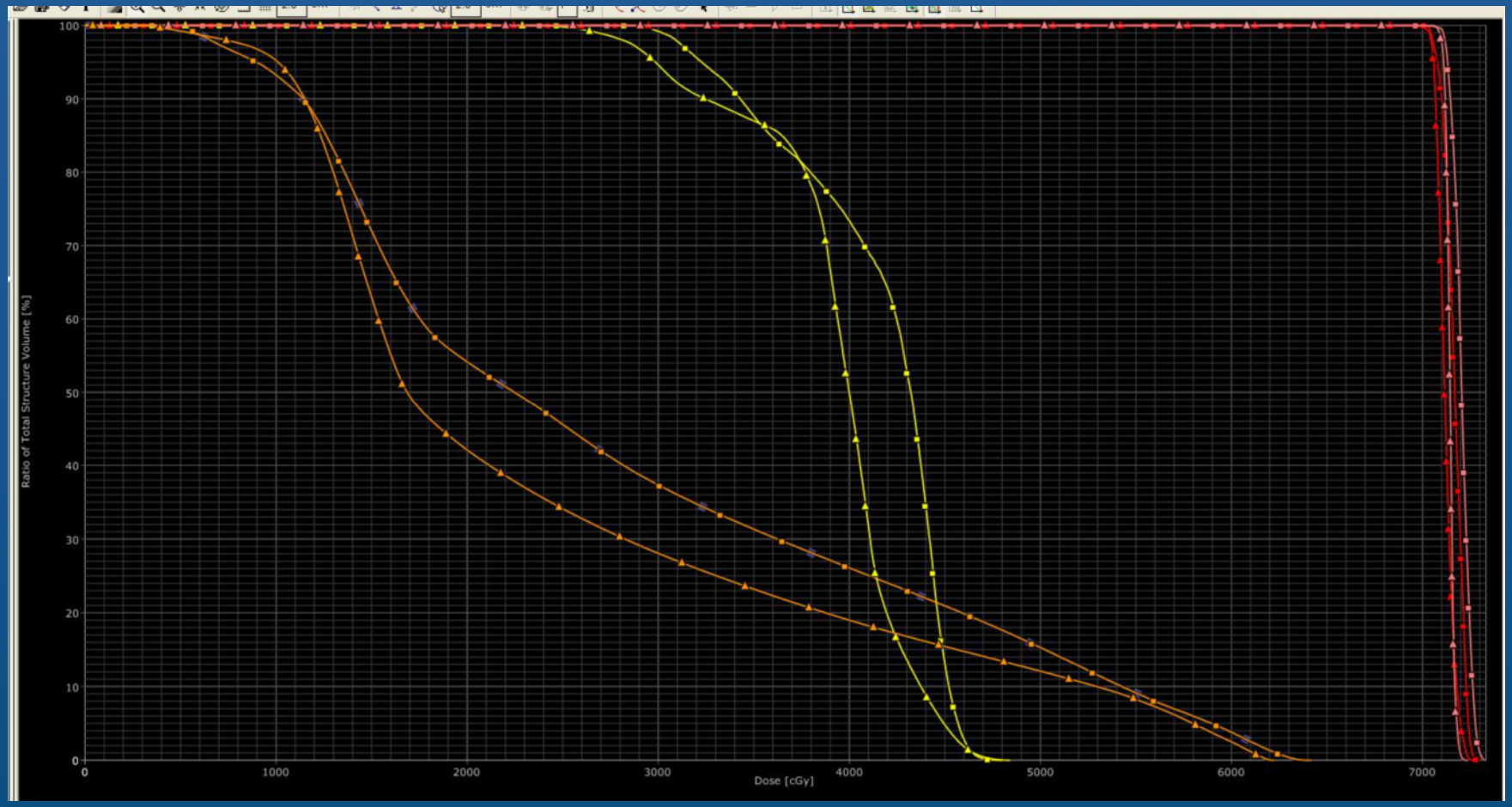
RapidArc Example: HN





This shows the comparison between a fixed field IMRT plan and a RapidArc plan for a head and neck case. Similar dose distributions, but the RapidArc plan can be delivered in 2 minutes.

RapidArc Example: HN DVH



Comparable plans, but RapidArc plan can be delivered in 2 minutes as opposed to 10 minutes for the IMRT plan

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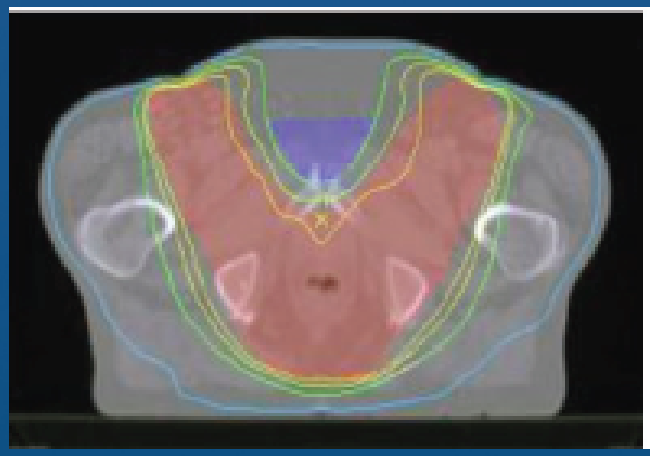
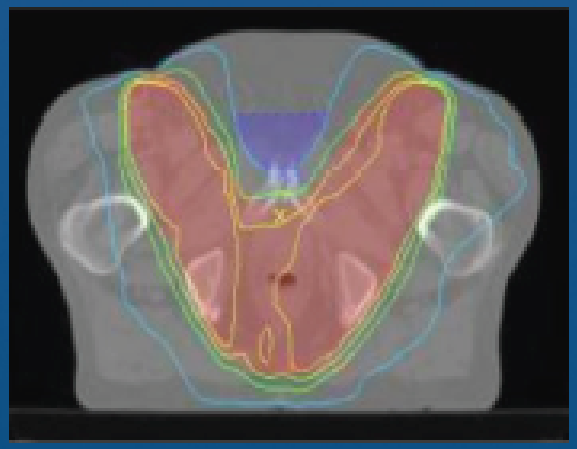
Elekta's Ergo++

1) Aperture based algorithm
2) Apertures are determined based on anatomy
3) Relative weights of apertures are optimized
4) Can do single arc or multi-arc



2 Rotations:
BEV and BEV-avoidance

1 Rotation:
BEV-avoidance when in front



1 Rotation:
BEV-avoidance

Anal case study from Universitatsklinikum Mannheim, Germany Klinik fur Strahlentherapie und Radioonkologie. From www.elekta.com

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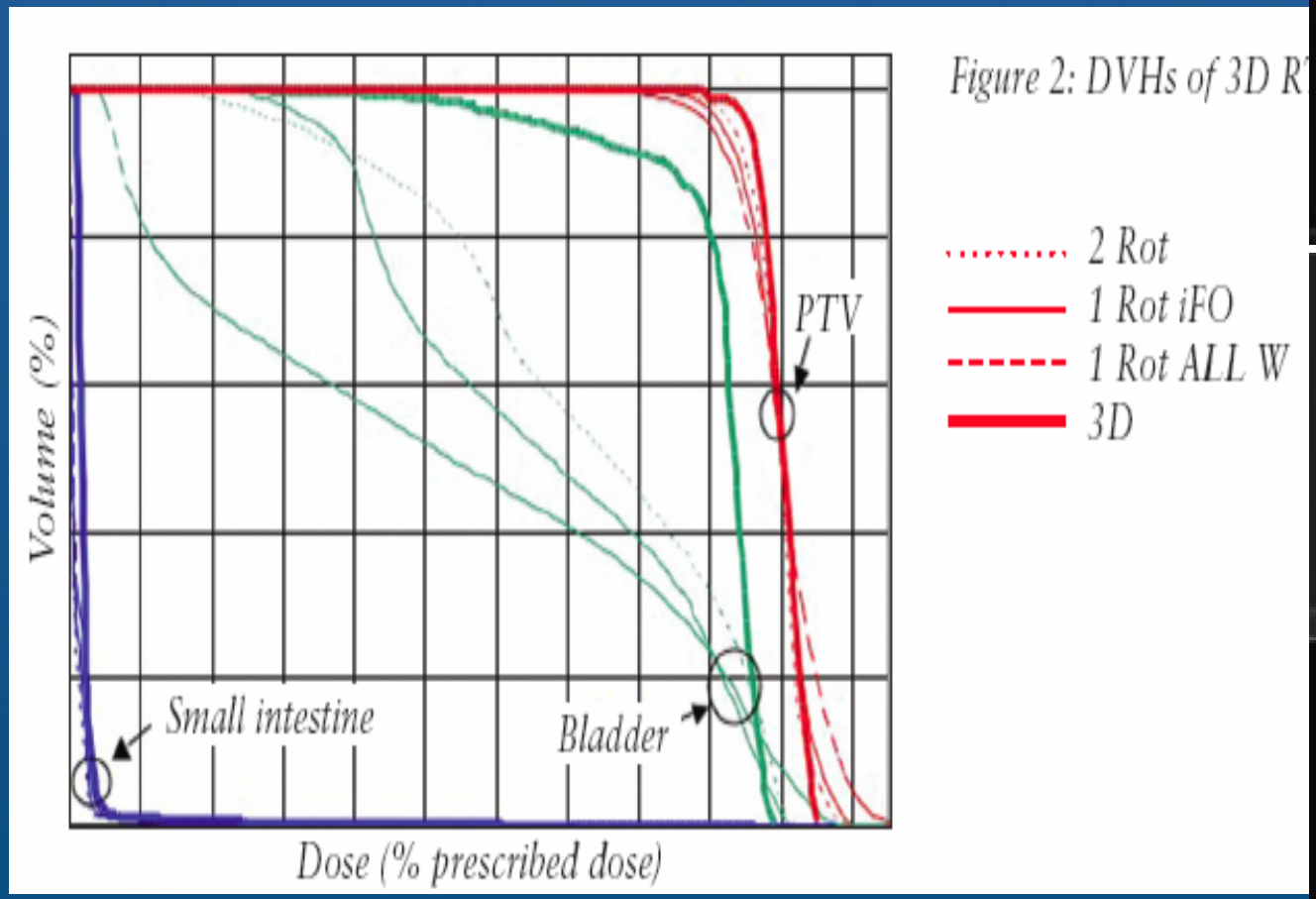
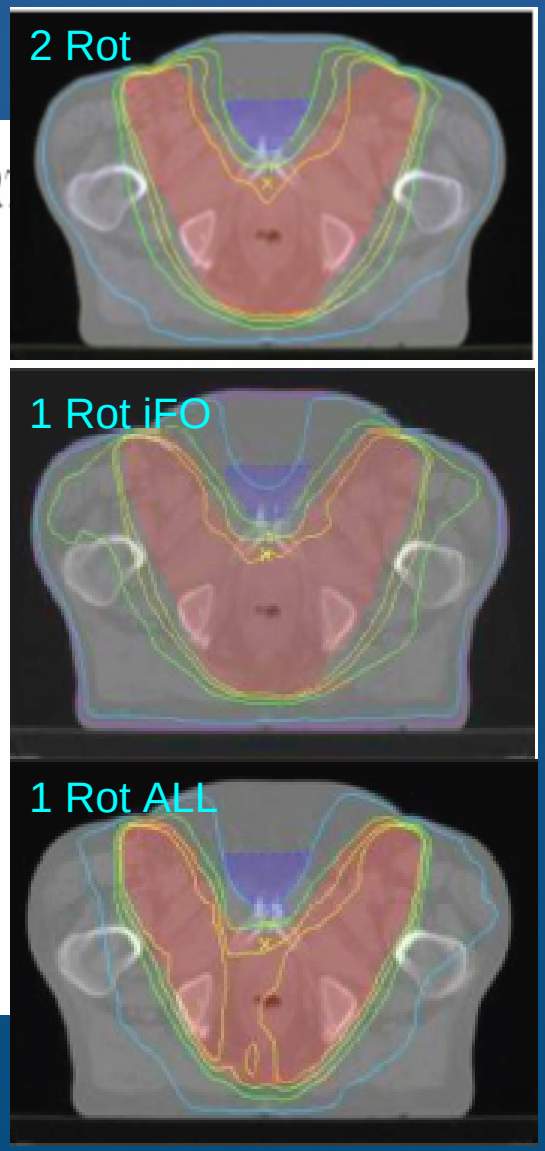
Ergo++: Anal DVH





Anal case study from Universitatsklinikum Mannheim, Germany Klinik fur Strahlentherapie und Radioonkologie. From www.elekta.com

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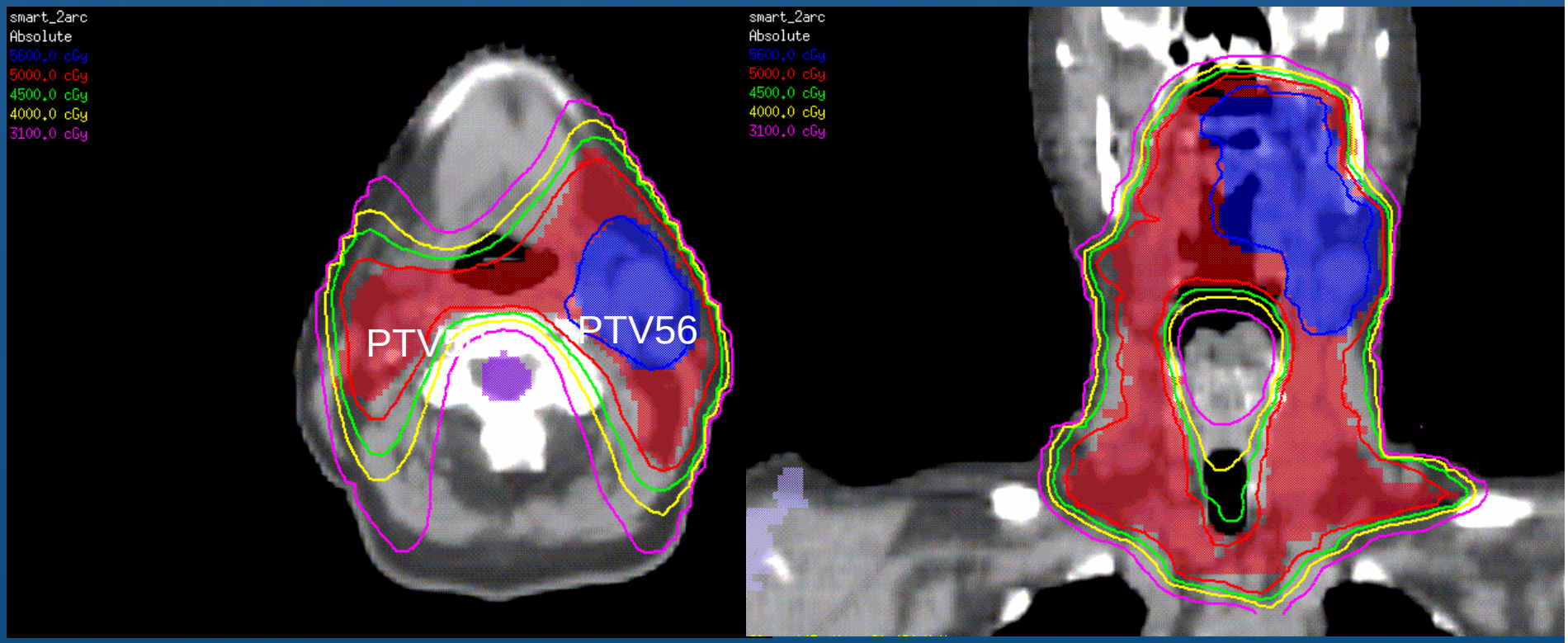
Philips SmartArc

1) Technique based on existing DMPO algorithm in Pinnacle
2) Will work with both Varian and Elekta



2 arcs, 640 MU, 1.8Gy, Delivery 4.5 minutes Elekta

Courtesy Dave Shepard
Swedish Cancer Institute

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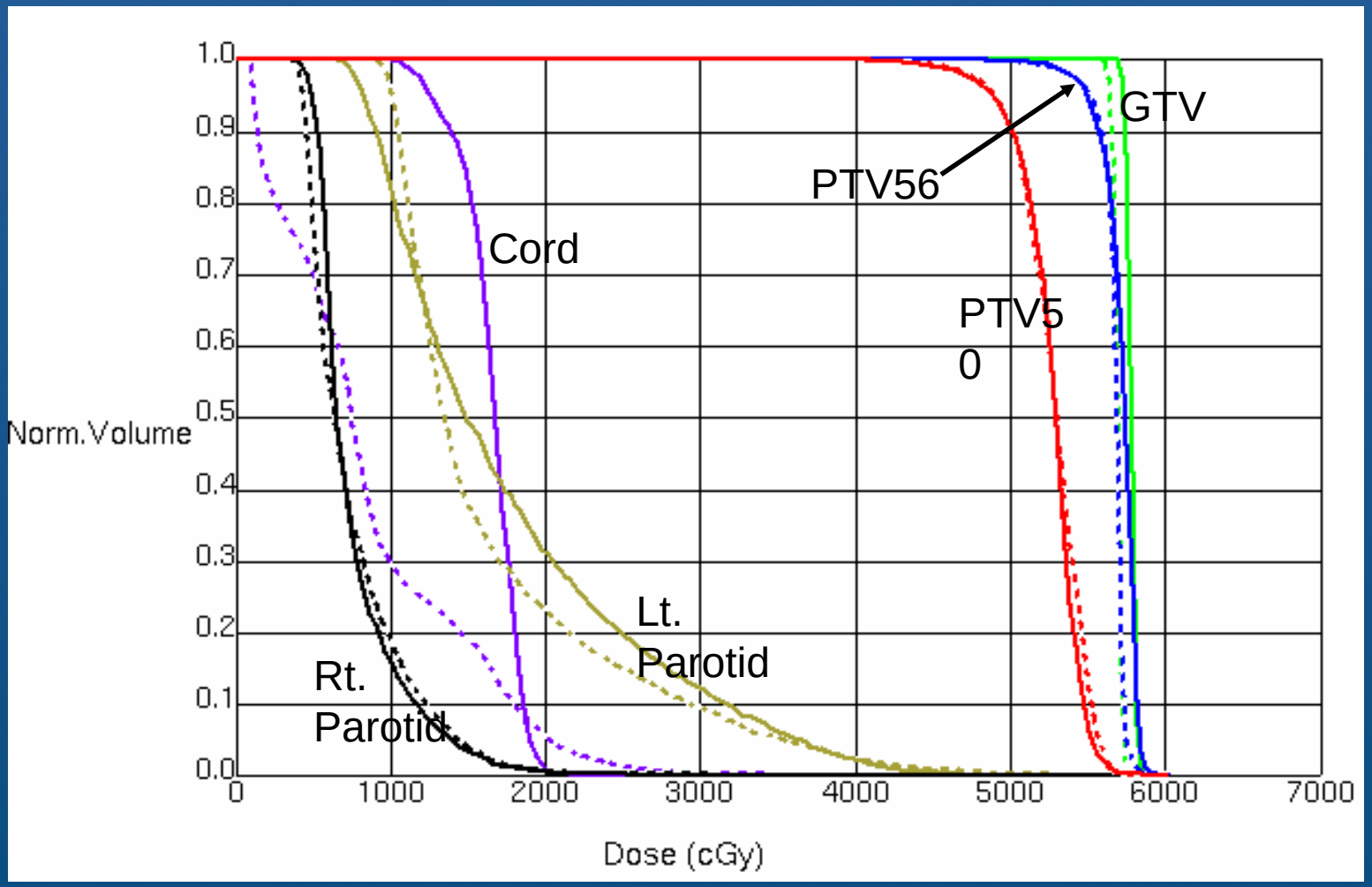
Philips SmartArc DVH



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Courtesy Dave Shepard
Swedish Cancer Institute

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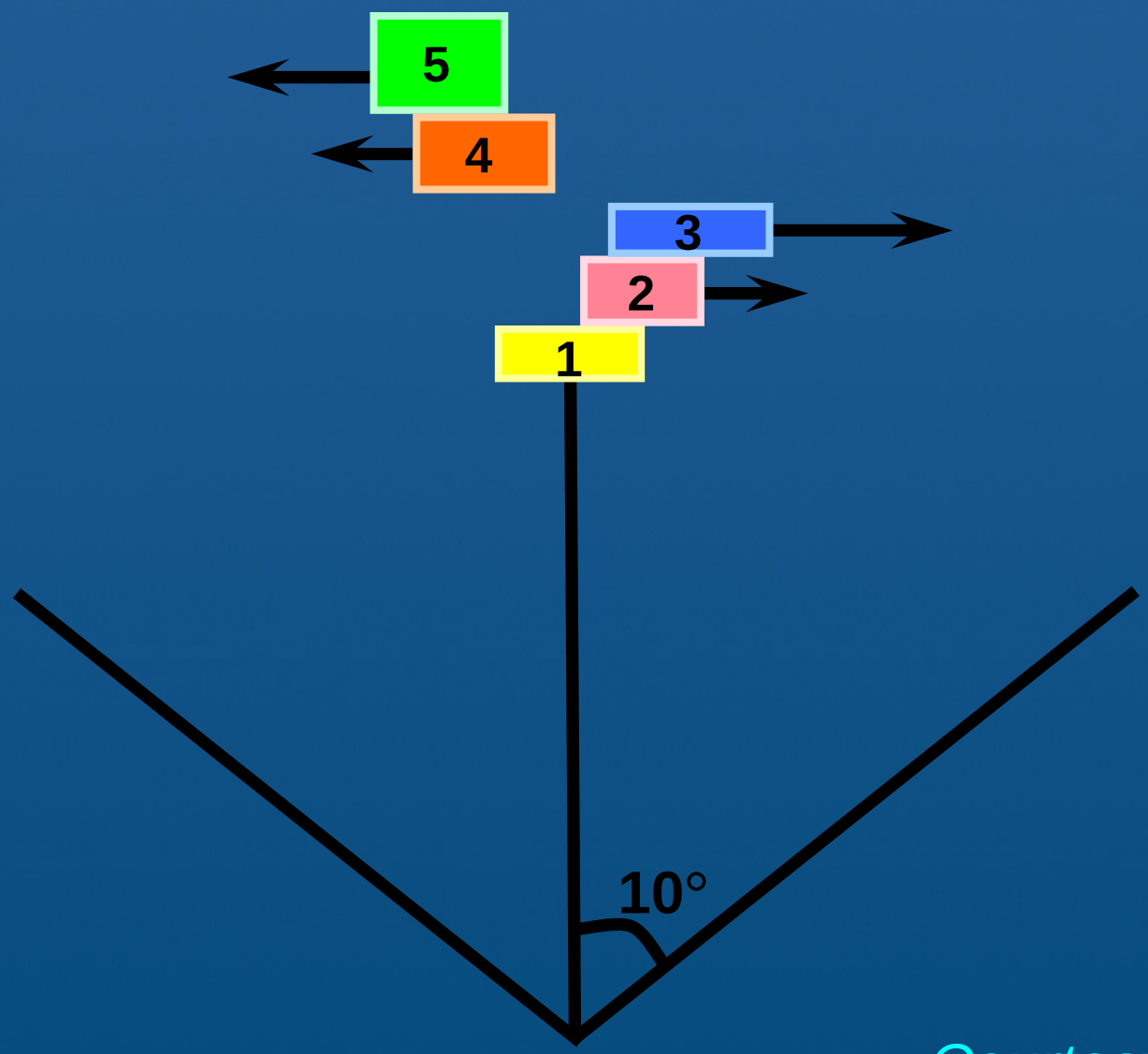
Converting multiple arcs into a single arc



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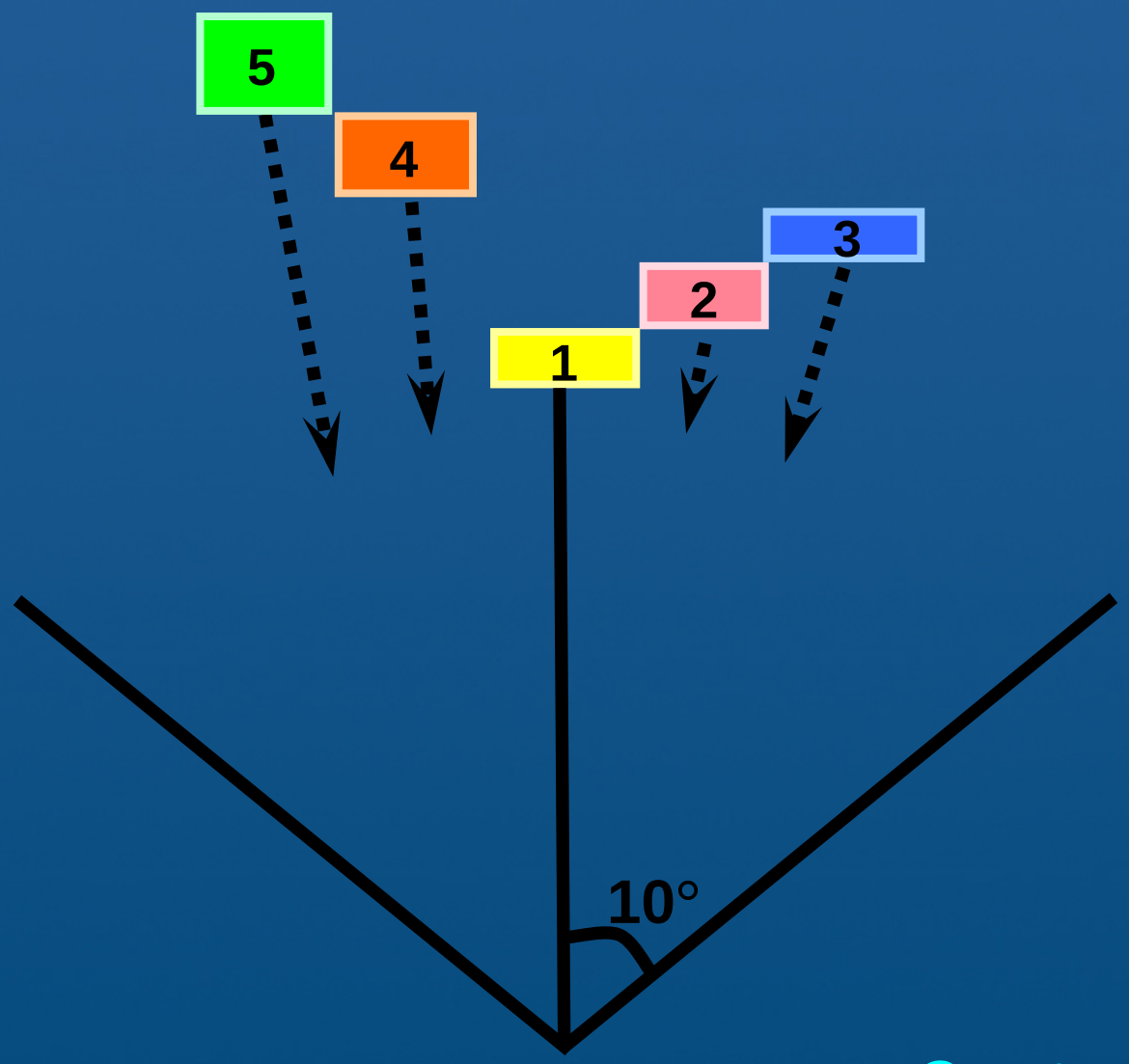
Courtesy Grace Tang

Converting multiple arcs into a single arc



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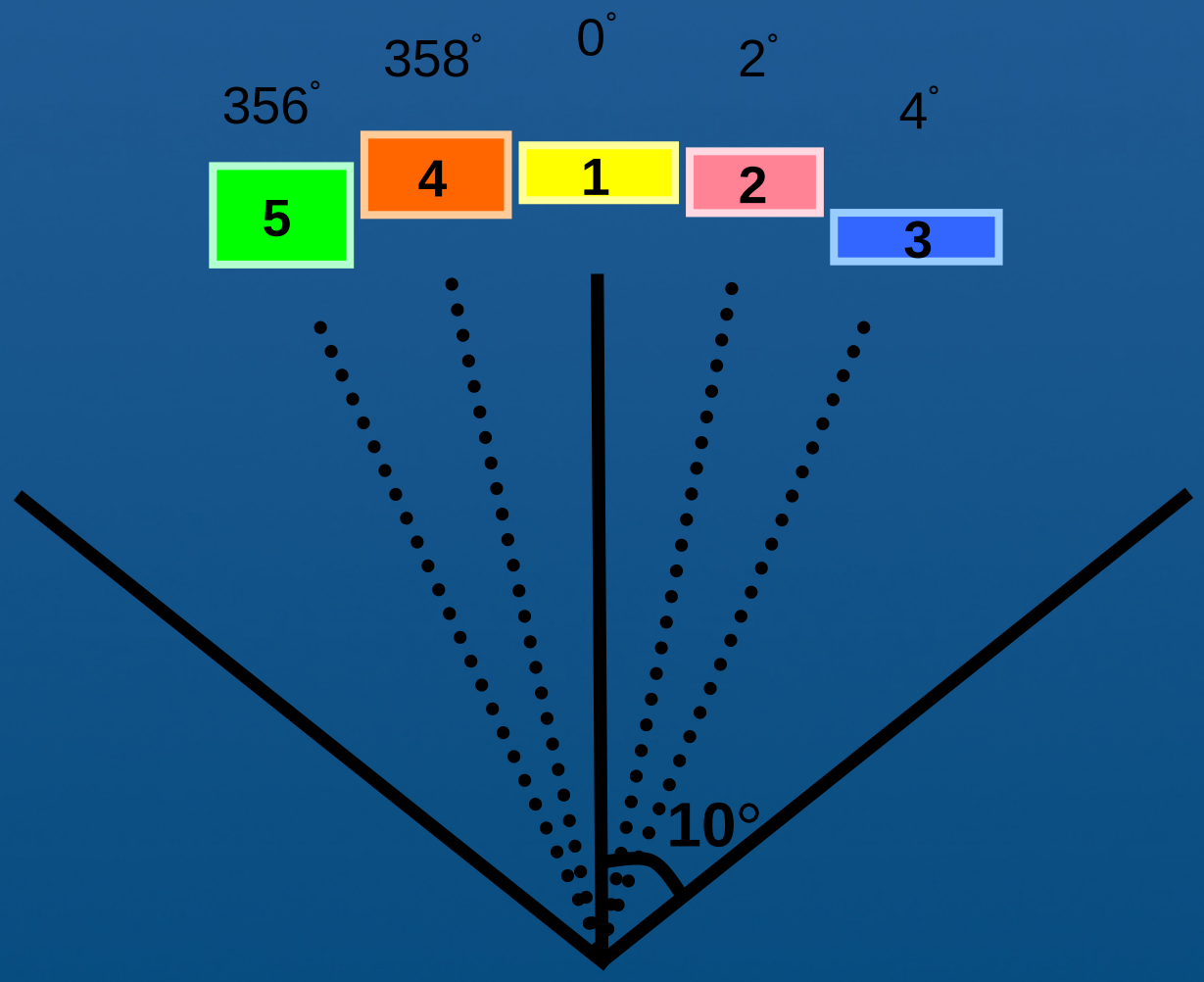
Courtesy Grace Tang

Converting multiple arcs into a single arc



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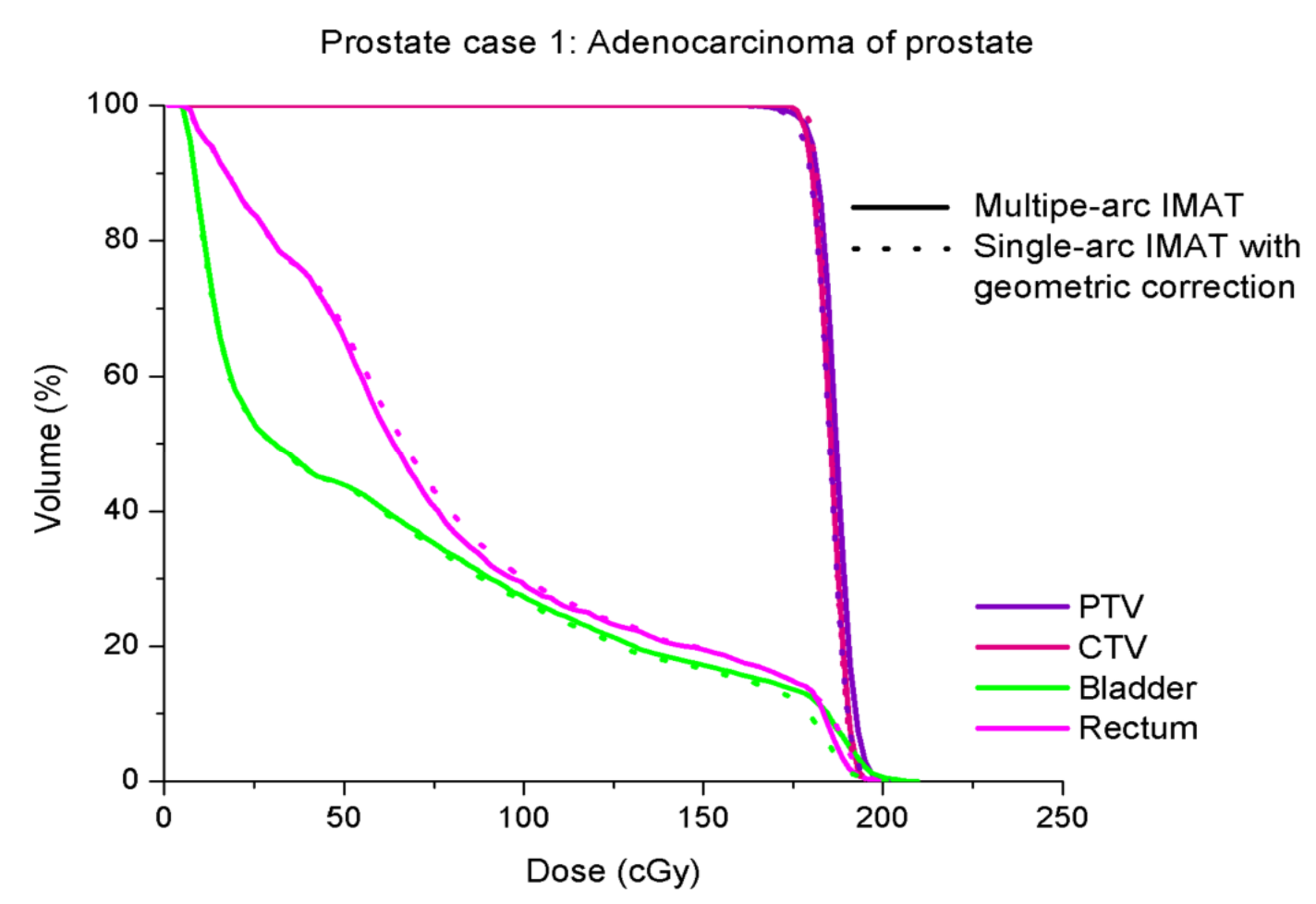
Courtesy Grace Tang

Spreading technique: Prostate



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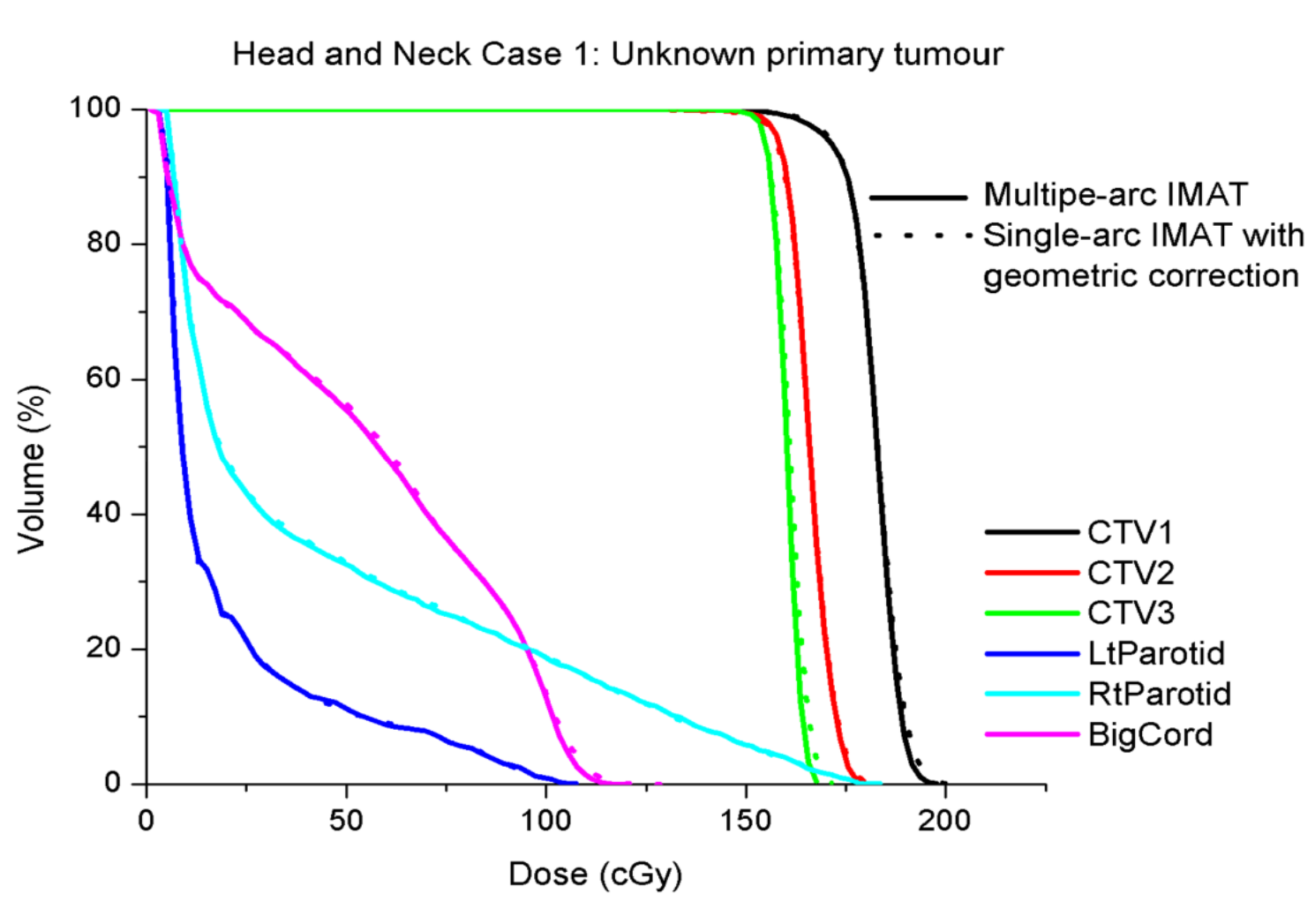
Courtesy Grace Tang

Spreading technique: Head and Neck



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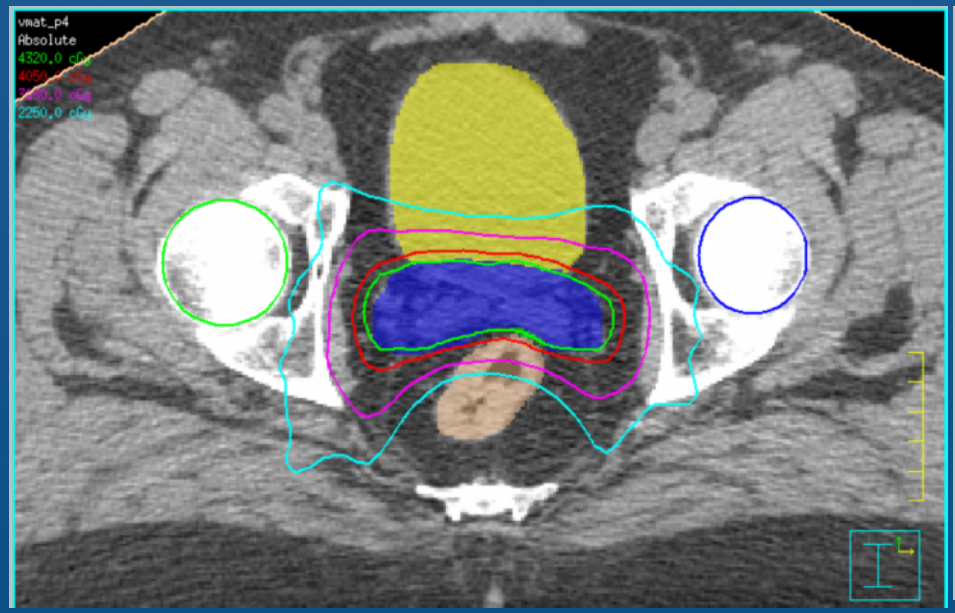
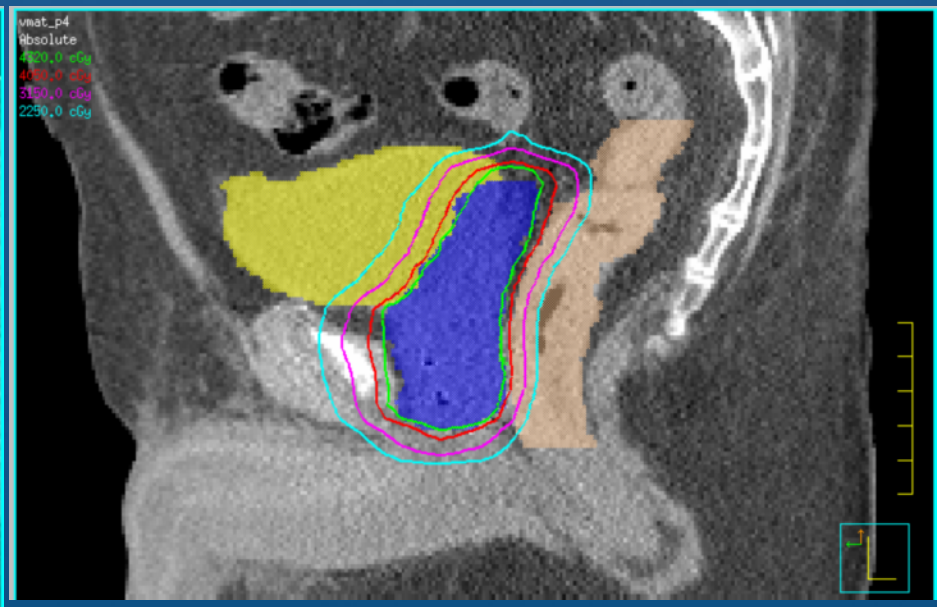
Courtesy Grace Tang

“CIMO” Single-arc

Can use the CIMO algorithm with single arc, incorporating delivery constraints into annealing sequencer. Optimization performed in Pinnacle





1) Single arc on Elekta Synergy
2) 562 MU
3) Delivery 2.5 minutes

Courtesy Dave Shepard
Swedish Cancer Institute

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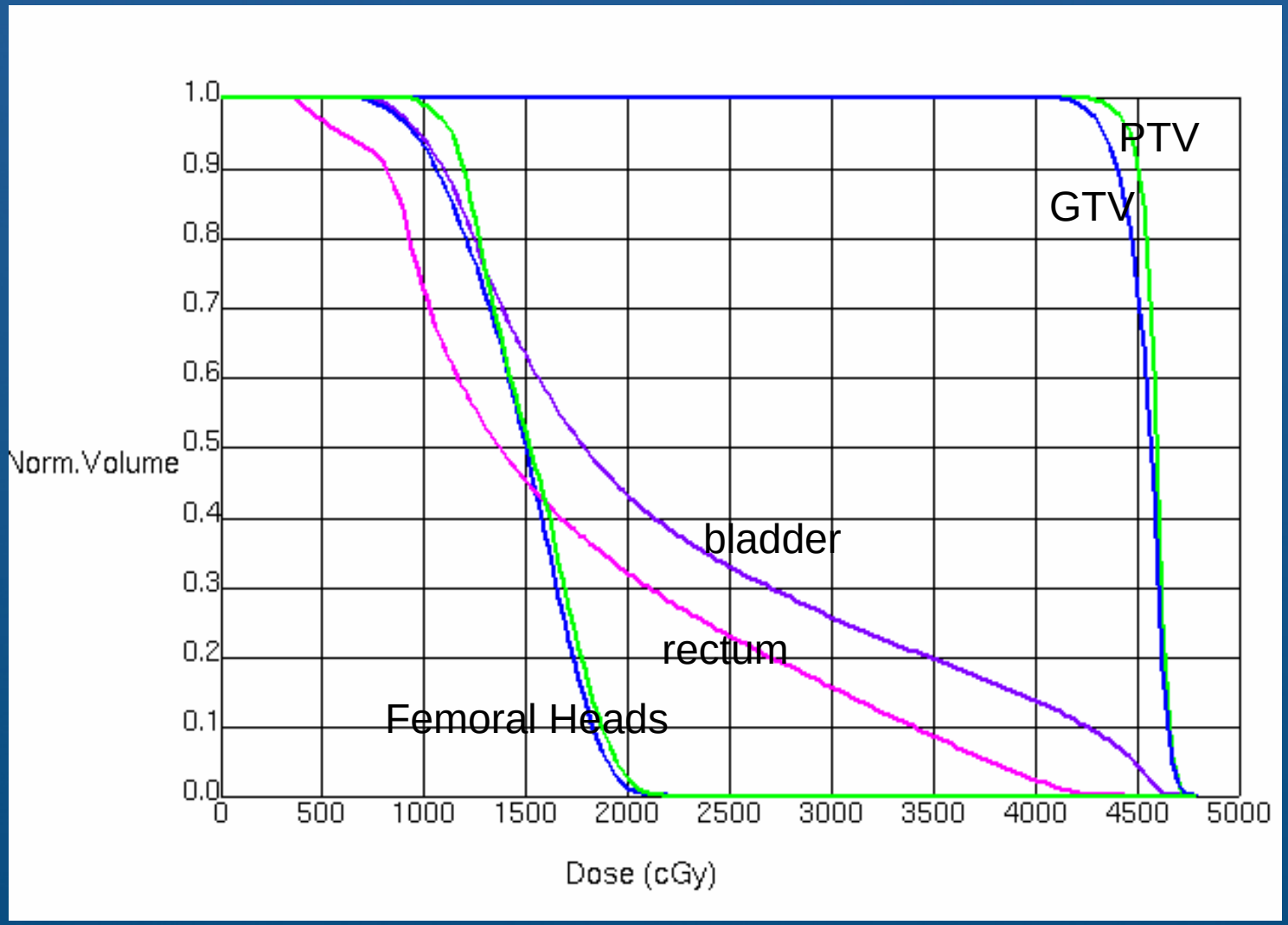
“CIMO” Single-arc DVH



Courtesy Dave Shepard
Swedish Cancer Institute

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Comparison

Several comparisons between multi-arc and single-arc have been done. (See 2008 AAPM meeting)

For example, E Wong *et al*, D Cao *et al*, G Tang *et al*

Some say that multi-arc produce better plans, others say a single-arc is sufficient.

Comparison: IMRT/IMAT/AMRT

COMPARISON OF RADIATION TREATMENTS USING INTENSITY-MODULATED BEAMS, MULTIPLE ARCS, AND SINGLE ARCS

Grace Tang, M.Phil.,*† Matthew A. Earl, Ph.D.,* Shuang Luan, Ph.D.,‡ Chao Wang, Ph.D.,§ ~~Shahid A. Naqvi, Ph.D.,*~~ Majid M. Mohiuddin, M.D.,* and Cedric X. Yu, D.Sc.*

Also, part was presented at AAPM 2008

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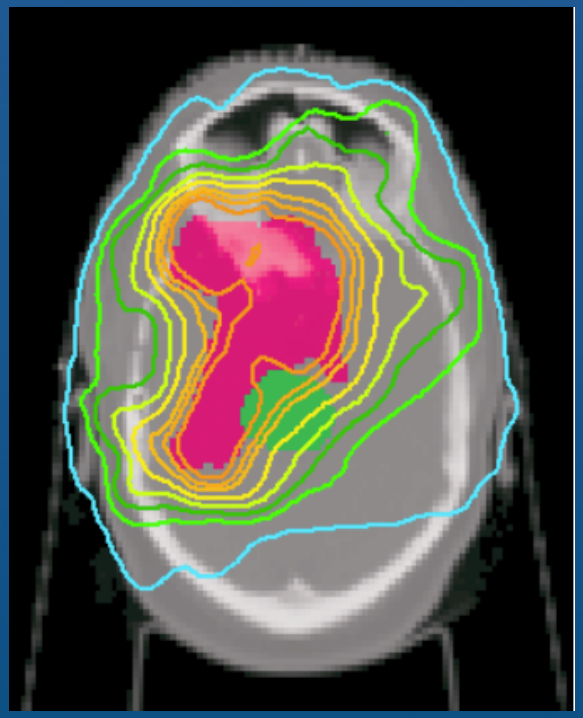
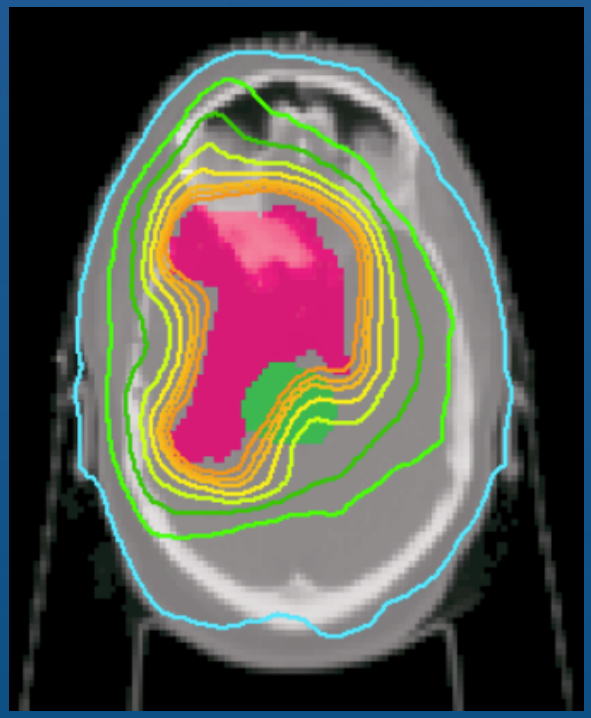
Courtesy G. Tang

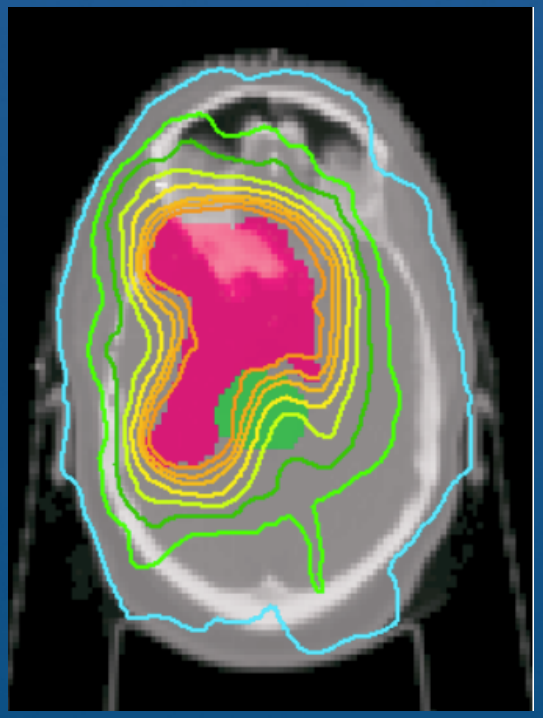
Comparison: IMRT/IMAT/AMRT Brain



IMRT



IMAT



AMRT

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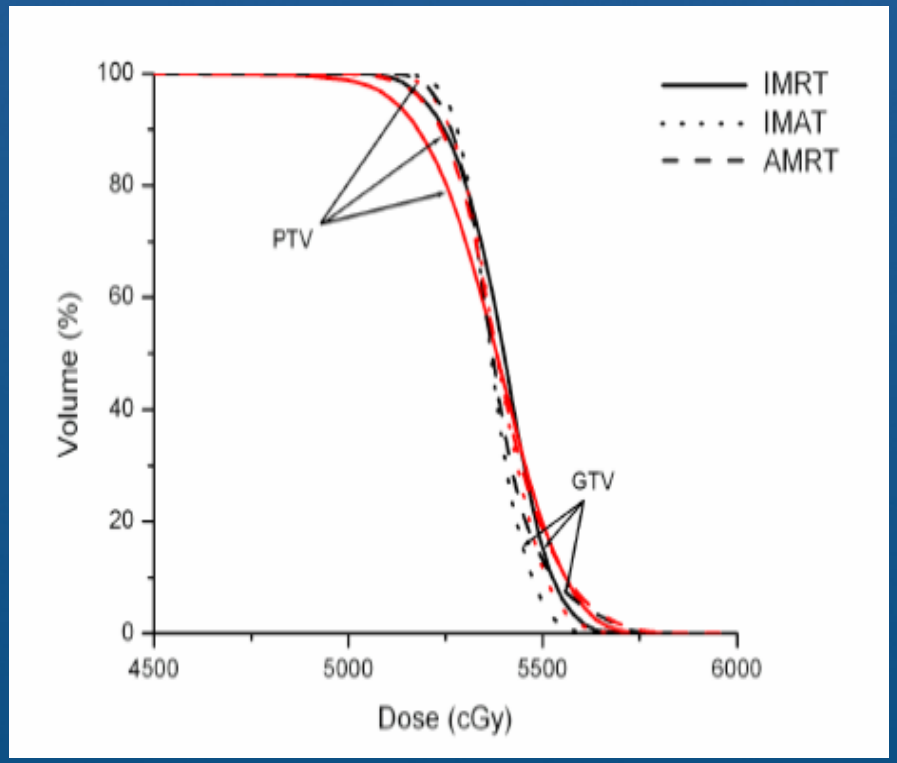
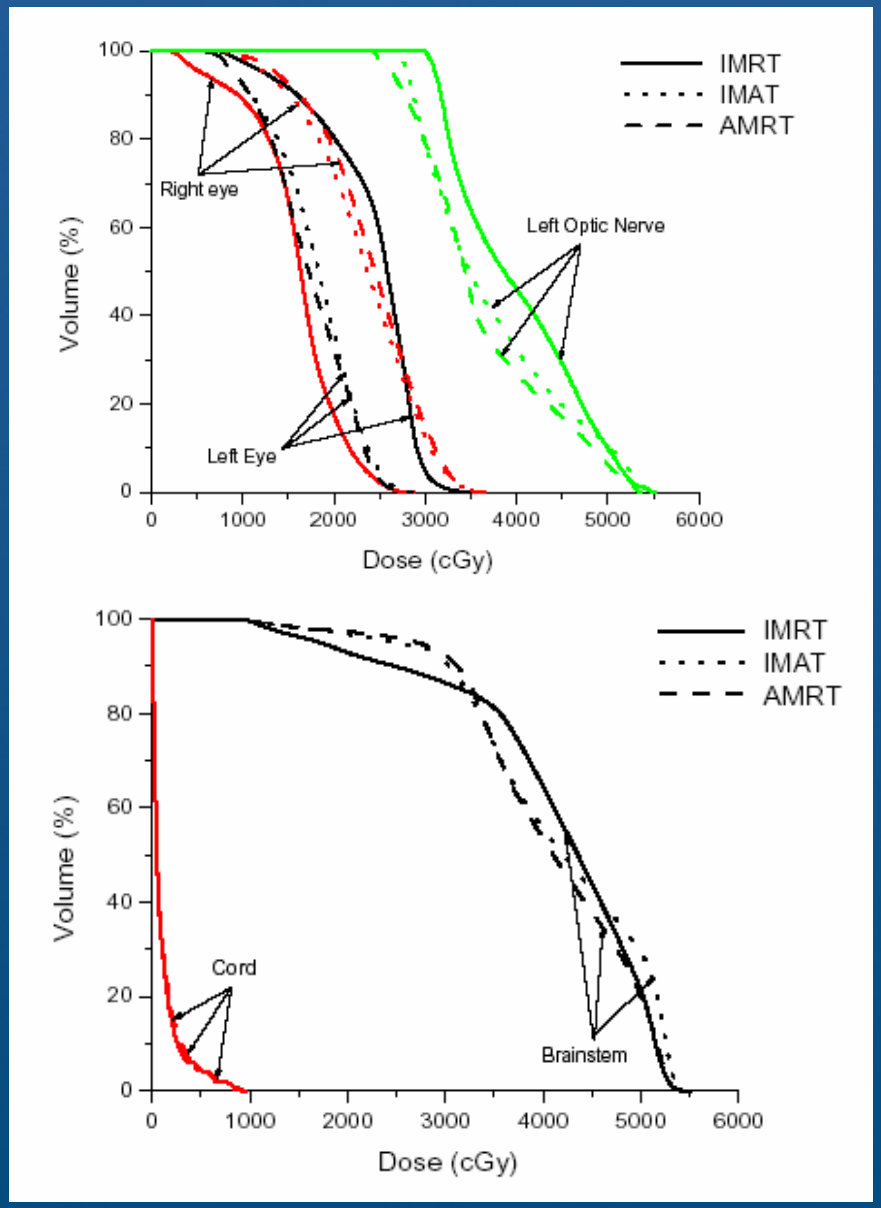
Courtesy G. Tang

Comparison: IMRT/IMAT/AMRT Brain





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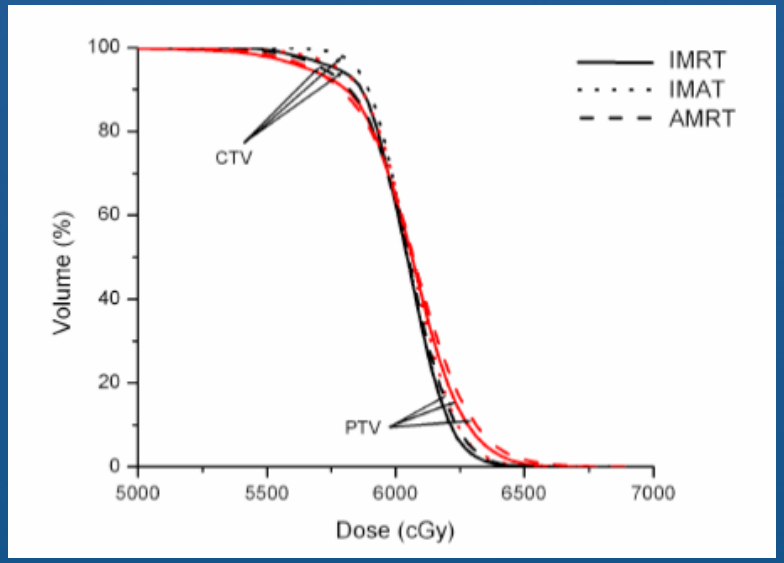
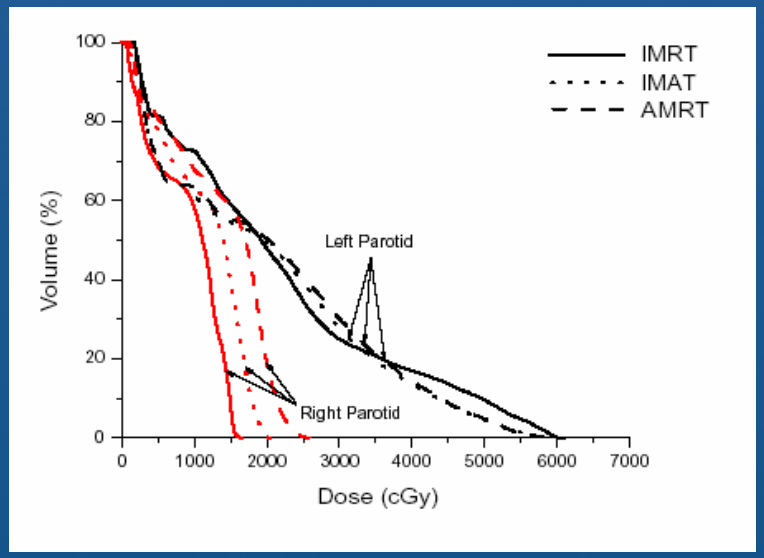
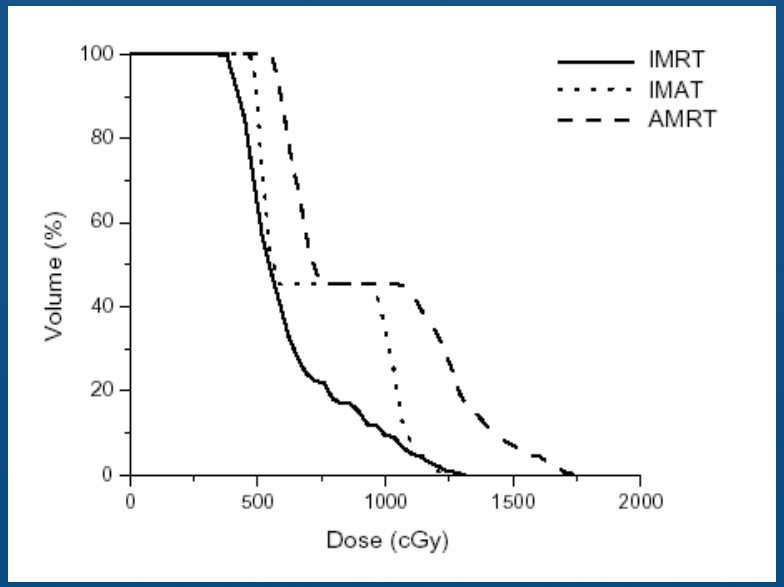
Courtesy G. Tang

IMRT/IMAT/AMRT: Head and Neck







Ultimately, multi-arc IMAT produces the best plan, but with longer delivery time

Courtesy G. Tang

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Summary

1. Recent advances in planning have resulted in the ability to plan linac-based rotational IMRT
2. Linac manufacturers have incorporated dose rate modulation which has resulted in improved treatment plan quality for rotational IMRT
3. Both aperture based and sequence based solutions exist
4. Commercial TP systems have begun to provide solutions for rotational IMRT
5. Still up for debate whether single rotation is comparable to multiple rotation

The End!!!

Please contact me for questions, etc.

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