IMRT Optimization Algorithms

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Swedish Medical Center

- Founded in 1910 by Dr. Nils Johanson and a group of Seattle's leading Swedish-born businessmen.

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Acknowledgments

- Rock Mackie
- Joe Deasey
- Daliang Cao
- Min Rao
- Thomas Bortfeld
- Nucletron
- Karl Otto

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Disclaimer

- We currently have a research grant sponsored by Elekta.

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Objectives

1) Provide an overview of the key concepts in IMRT plan optimization.
2) Review inverse planning techniques used for fixed field IMRT, VMAT, and tomotherapy.
3) Examine new optimization tools such as multicriteria optimization.

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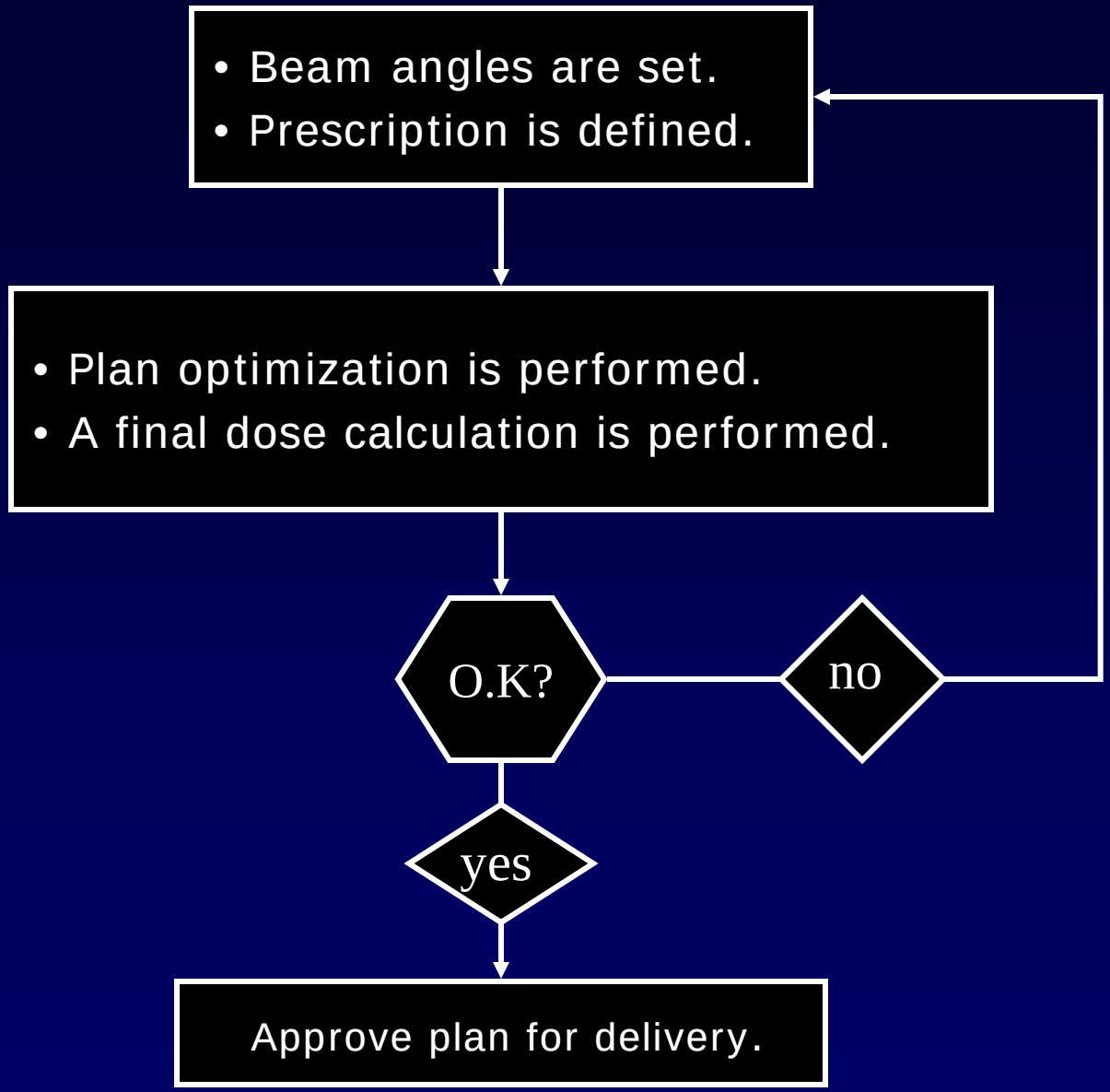
Outline

1. The IMRT planning process
2. Defining treatment plan goals
3. Plan optimization
4. Future developments

1. The IMRT Planning Process


• Beam angles are set.
• Prescription is defined.
• Plan optimization is performed.
• A final dose calculation is performed.
O.K?
no
yes
Approve plan for delivery.

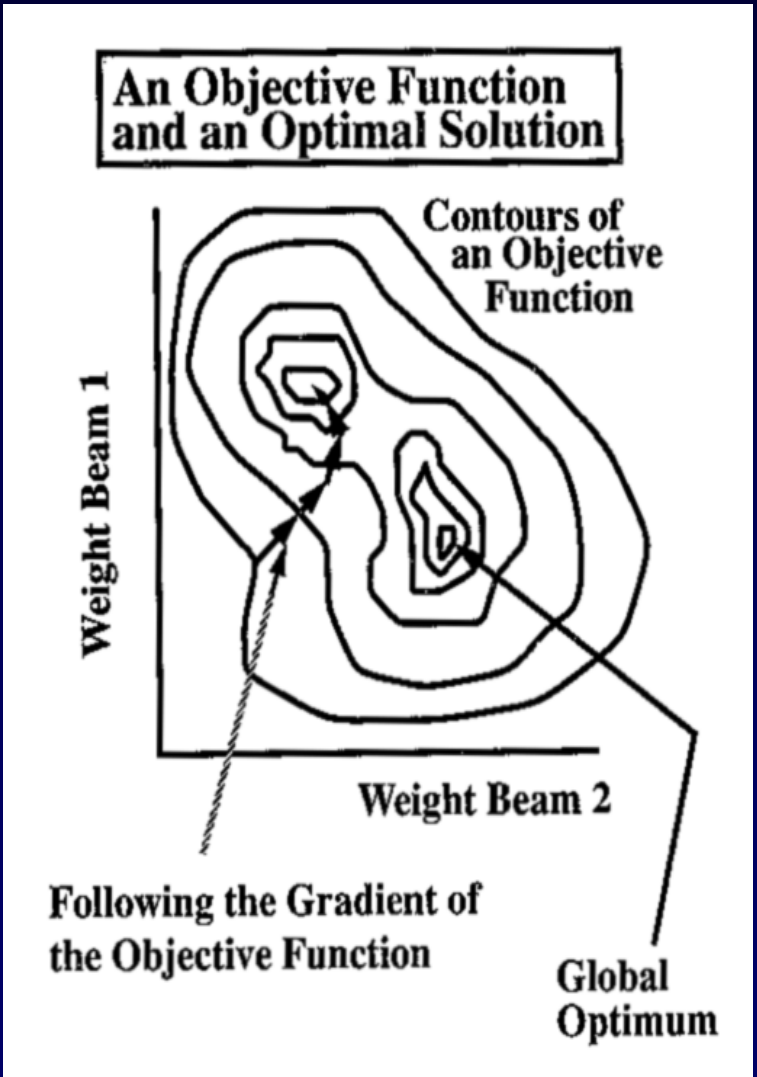
2. Defining the prescription

- The prescription defines the goals of the treatment.
- The goals can be expressed in the objective function or the constraints.
- The plan quality can be scored using either physical or biological criteria.

Prescription Challenge

- It is difficult to reduce all of our treatment planning goals into a set of equations or a single scoring function.

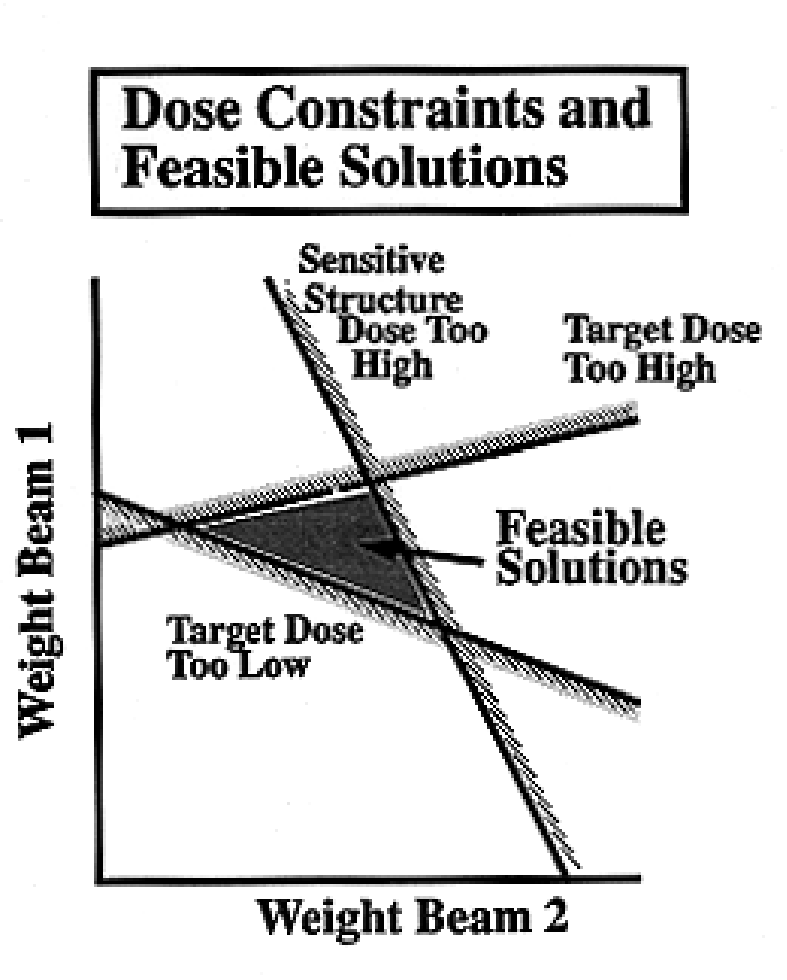
Objective Function



- The objective function reduces the entire treatment plan into a single numerical value that scores the quality of the plan.
- This has the same advantages and limitations as assigning a numerical grade in a course. It allows ranking to be done but it may not adequately define the overall intent.

Courtesy of Rock Mackie

Constraints



- Constraints place restrictions on the set of solutions that are considered feasible.
- Constraints define what is an acceptable solution. They do not define what is an optimal solution.
- When conflicting constraints arise, there may not be any feasible solution.
- The most basic constraint in IMRT is that all of the beam weights must be nonnegative.

Courtesy of Rock Mackie

Dosimetric Objective Functions/Constraints

Dosimetric (Physical) Objectives/Constraints

- Criteria than can be expressed in terms of well defined physical quantities, such as dose and volume.

From Thomas Bortfeld

Dosimetric Constraints

- Target
  - minimum dose
  - maximum dose
- Sensitive Structures
  - maximum dose
  - mean dose
  - DVH constraints
    - no more than “x” % of the structure can exceed a dose of “y”.

Dosimetric Objectives

- Minimize sum of absolute differences between prescribed and delivered doses.
- Minimize sum of quadratic difference between prescribed and delivered dose.
- Minimize a weighted integral dose.
- Maximize the minimum dose to the target.

Advantages and Disadvantages of Dosimetric Objective Functions and Constraints

Minimum/Maximum Dose

Advantages

- Constraints can be used guarantee adequate dose uniformity in the tumor.
- Useful for serial structures such as the spinal cord.

Minimum/Maximum Dose

Disadvantages

- Allowing small hot and/or cold spots are often provide a significant improvement in dose conformity.
- One point can dominate the optimization.
- If target and RAR are in close proximity, these constraints often cannot be satisfied.

Mean Dose

Advantages

- Easy to formulate.

Disadvantages

- Of limited value for most sensitive structures.
- Dramatically different dose distributions can have the same mean dose.

$(Dose_{prescribed} - Dose_{delivered})^2$

Advantages

- Simple formulation.
- Higher penalty placed on outliers.
- Used in most commercial planning systems.

Disadvantages

- May not sufficiently penalize underdosage in the target.

DVH Based Penalties/Constraints

Advantages

- Good fit with clinical practices.
- Allows a portion of a sensitive structure to be overdosed in order to achieve adequate tumor dose coverage.

DVH Based Penalties/Constraints

Disadvantages

- True DVH constraints necessitate binary variables (MIP formulation).
- Highly nonlinear.
- Multiple DVH constraints are often necessary to meet user's objectives.

Biological Objective Functions and Constraints

Biological Objectives/Constraints (1)

- Biological objective functions and constraints are outcome related.
- Biological models are used to predict treatment outcome.

Biological Objectives/Constraints (2)

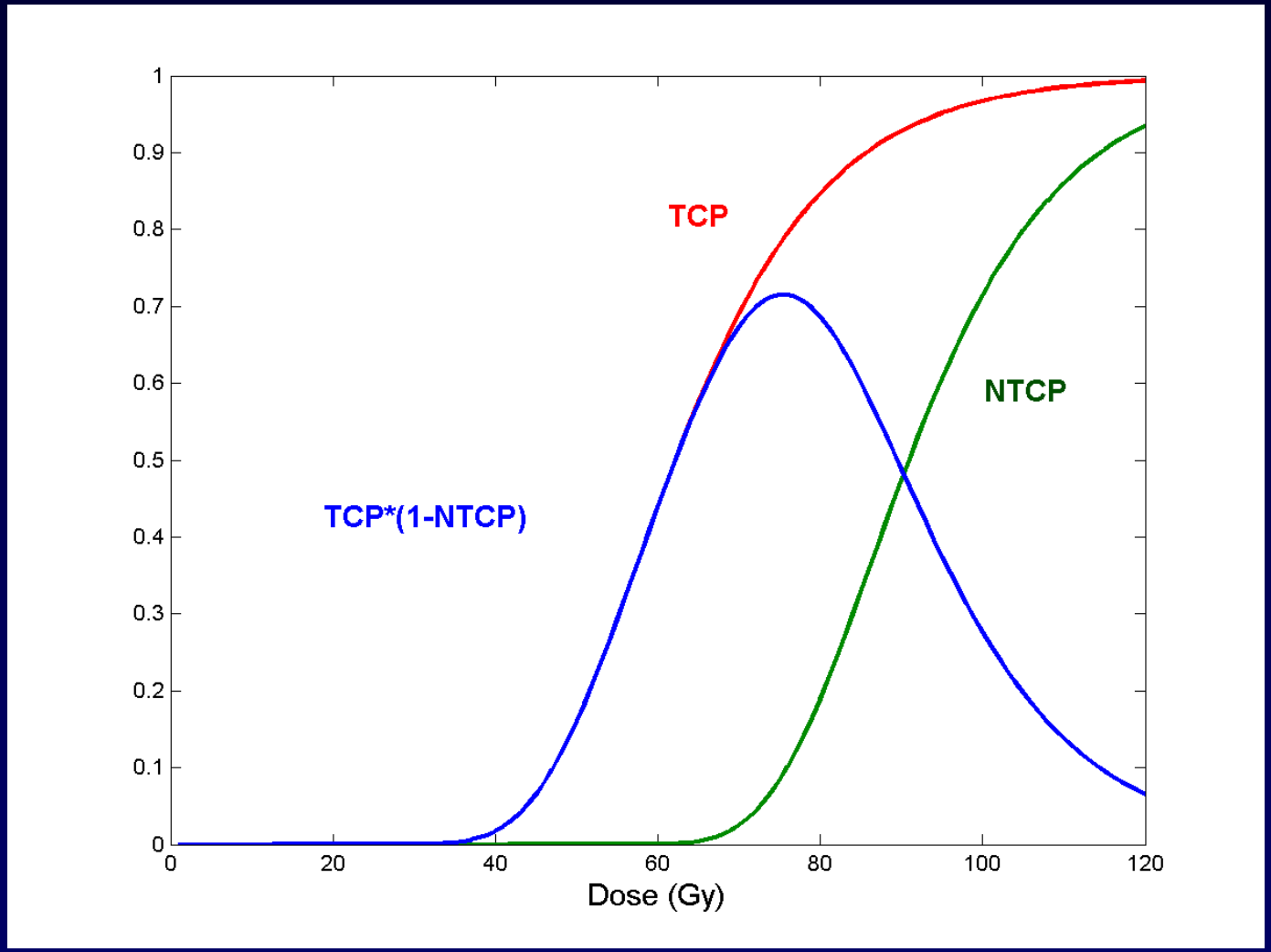
- Tumor Control Probability (TCP).
- Normal Tissue Complication Probability (NTCP).
- Uncomplicated TCP (UTCP or P+).
- Equivalent Uniform Dose (EUD).

Biological Objectives/Constraints (3)

- Tumor control probability (TCP). The probability of local control given the planned dose distribution.
- Normal Tissue Complication Probability (NTCP). The probability of some defined undesirable effect on the patient due to the irradiation.

From Joe Deasy

TCP and NTCP as a Function of Dose



Holthusen (1936)

Courtesy of Joe Deasy

Equivalent Uniform Dose (EUD)

- Two dose distributions are equivalent if the corresponding biological/clinical outcomes are equivalent.

Equivalent Uniform Dose (EUD)

- Based on the power law
- Normal structures and targets.

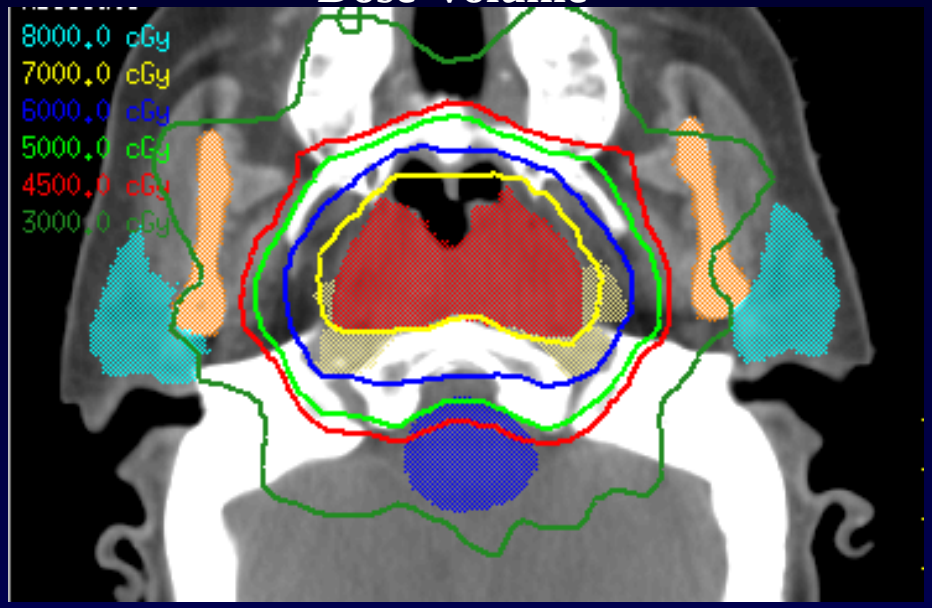
$$EUD = \left(\sum_{i=1} v_i D_i^a \right)^{\frac{1}{a}}$$

*Niemierko A. Med Phys, 26(6), 1999.

Equivalent Uniform Dose (EUD)

Structure (Source)	End-point	a
Chordoma base of skull (MGH)	Local control	-13
Squamous cc (Brenner)	Local control	-13
Melanoma (Brenner)	Local control	-10
Breast (Brenner)	Local control	-7.2
Parotids (Eisbruch)	Salivary function (<25%)	<0.5
Parotids (Chao)	Salivary function (<25%)	0.5
Liver (Lawrence)	Liver failure	0.6
Liver (Dawson)	Liver failure	0.9
Lung (Kwa)	Pneumonitis	1.0
Lung (Emami)	Pneumonitis	1.2
Kidney (Emami)	Nephritis	1.3
Liver (Emami)	Liver failure	2.9
Heart (Emami)	Pericarditis	3.1
Bladder (Emami)	Symptomatic contracture	3.8
Brain (Emami)	Necrosis	4.6
Colon (Emami)	Obstruction/perforation	6.3
Spinal cord (Powers)	White matter necrosis	13
Esophagus (Emami)	Perforation	18
Spinal cord (Schultheiss)	Paralysis	20

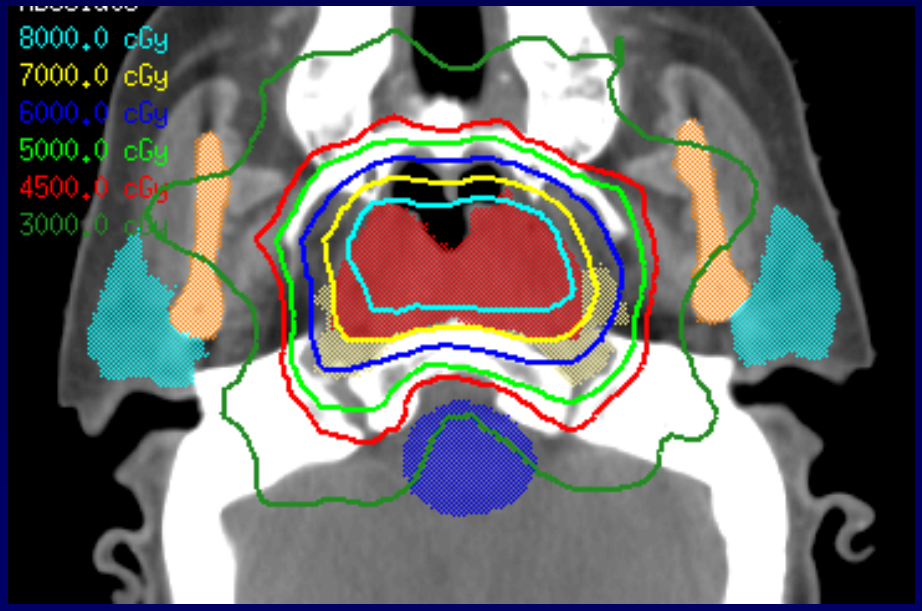
Dose-Volume



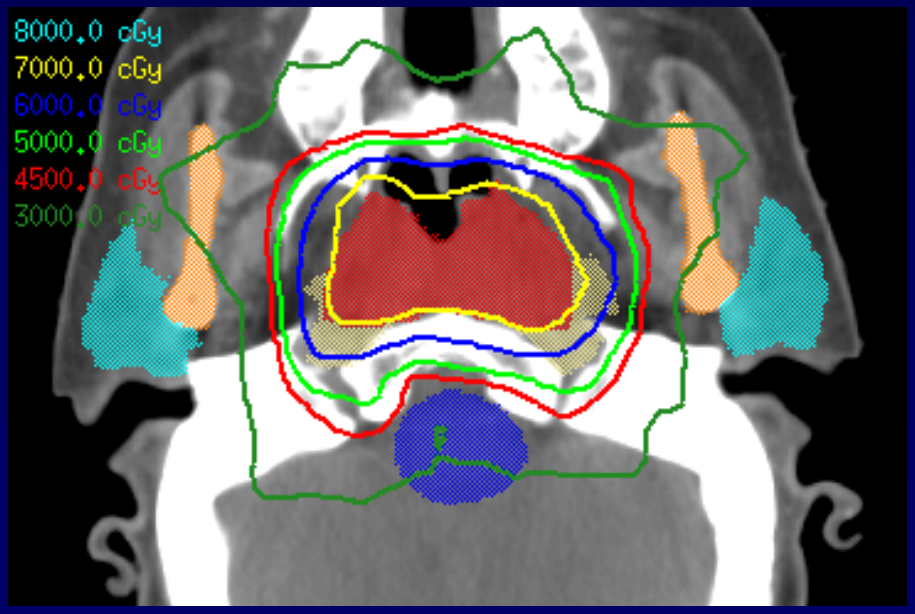
EUD Based Optimization

Wu, Mohan, Niemierko, Schmidt-Ullrich, Optimization of IMRT plans based on the equivalent uniform dose. Int J Radiat Oncol Biol Phys, 2002. 52(1))

EUD - unconstrained



EUD + tumor as "virtual normal tissue"



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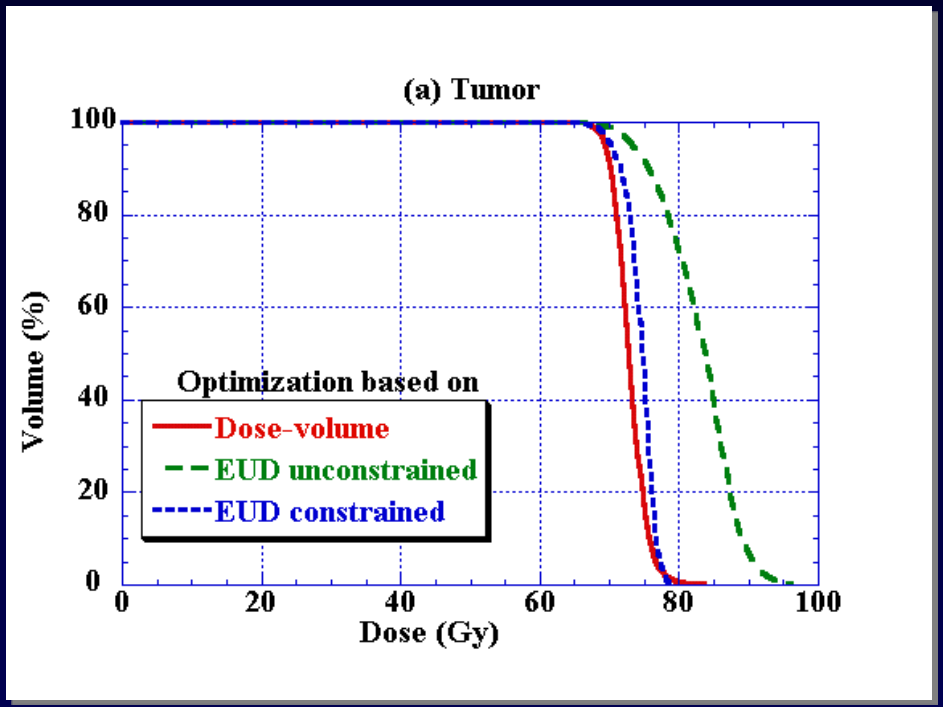
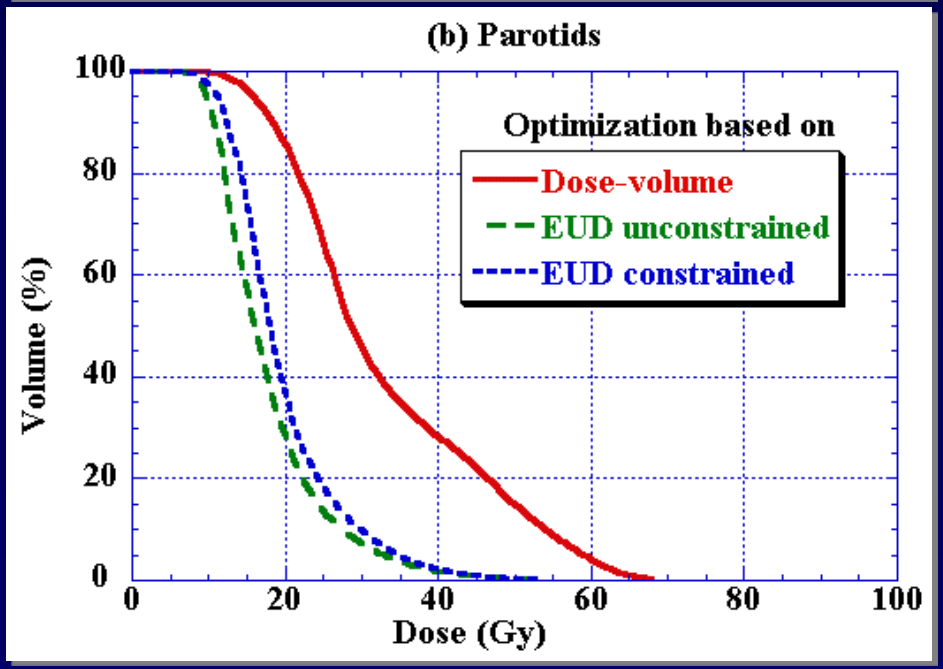
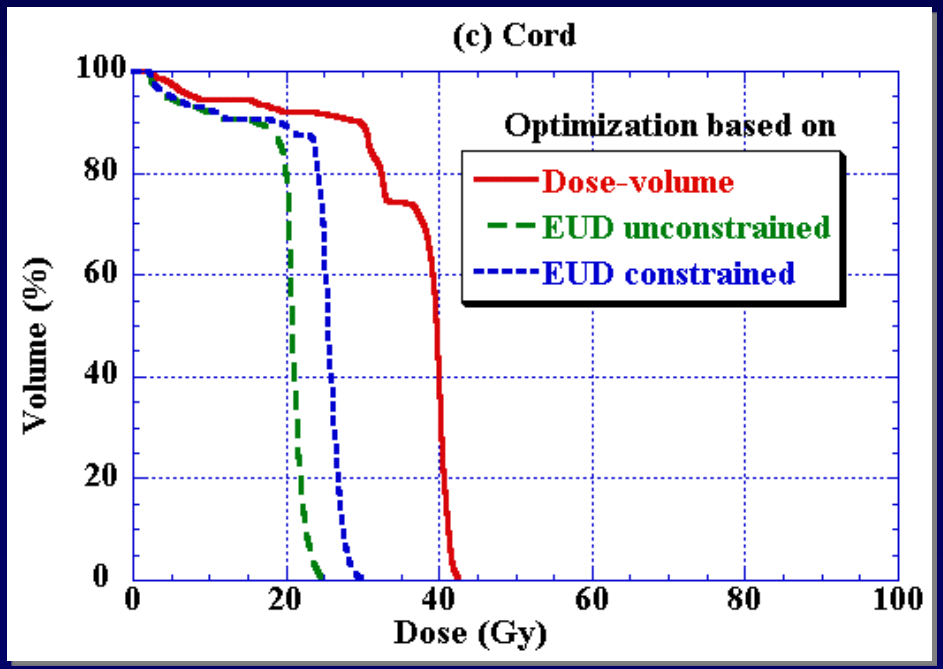






Biological Constraints

- Minimum TCP/EUD/P+.
- Maximum NTCP.

Biological Objectives

- Maximize TCP/EUD/P+.
- Minimize NTCP.

Biological Objectives/Constraints

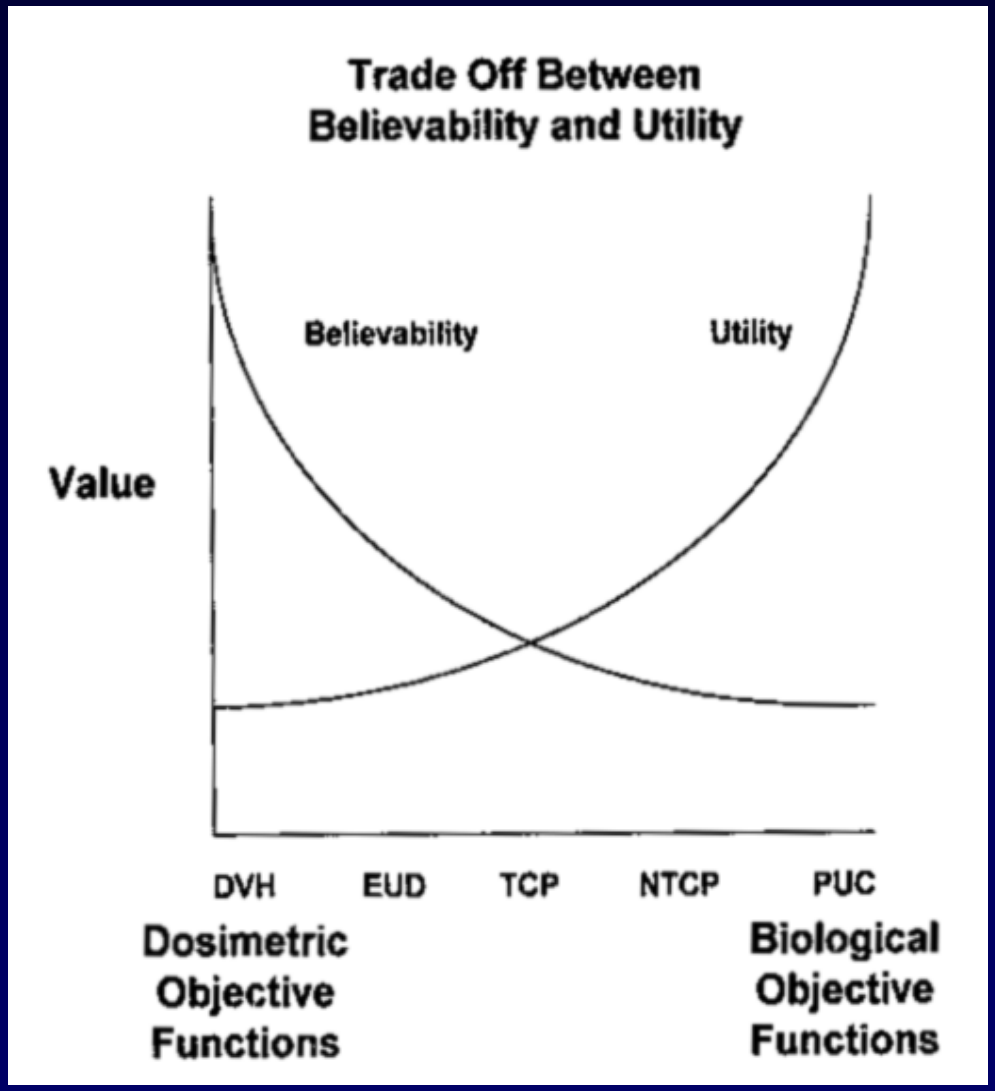
Advantages

- Our goal is to improve patient outcome, and this is precisely what is modeled with these techniques.

Disadvantages

- Because of uncertainties in the parameters included in the models, the accuracy of the models is often called into question.

Physical vs. Biological Objective Functions

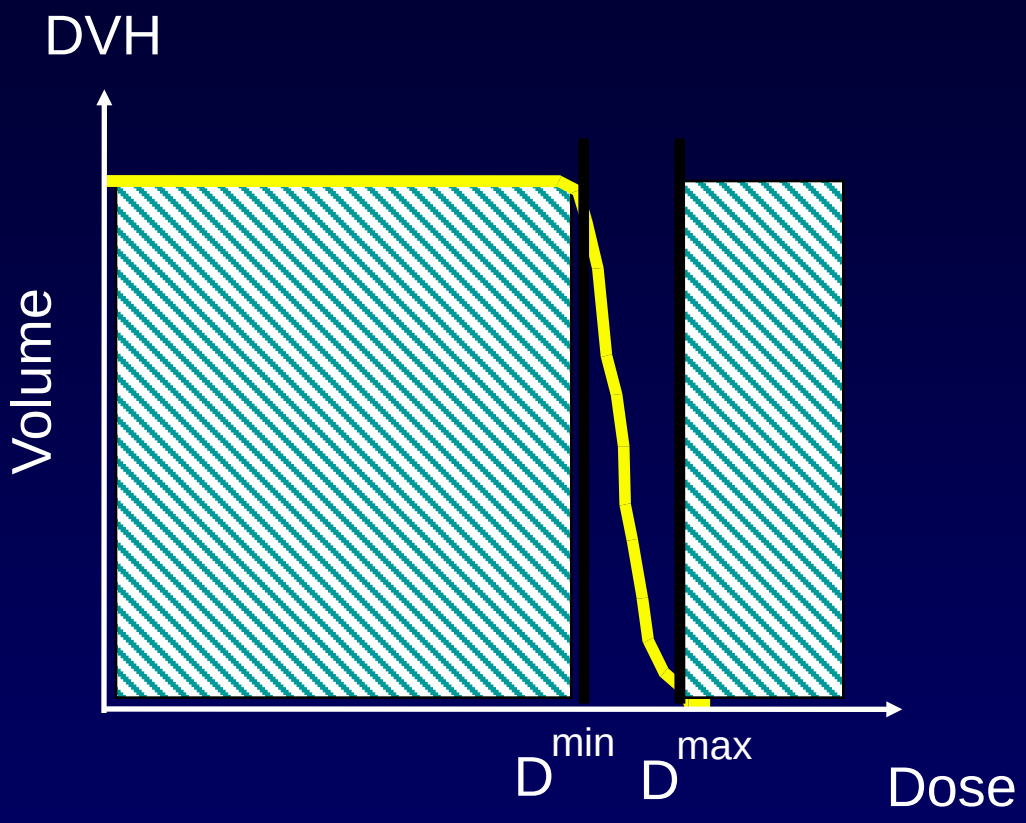


Courtesy of Rock Mackie

Typical Formulation in a Commercial TPS

- Minimizes a sum of weighted least squares deviations from the defined goals.
- The goals include:
  - minimum and maximum target dose
  - maximum dose for each sensitive structure
  - DVH based treatment goals
- By increasing the relative weight assigned to a particular goal, you can increase the probability of meeting that goal.

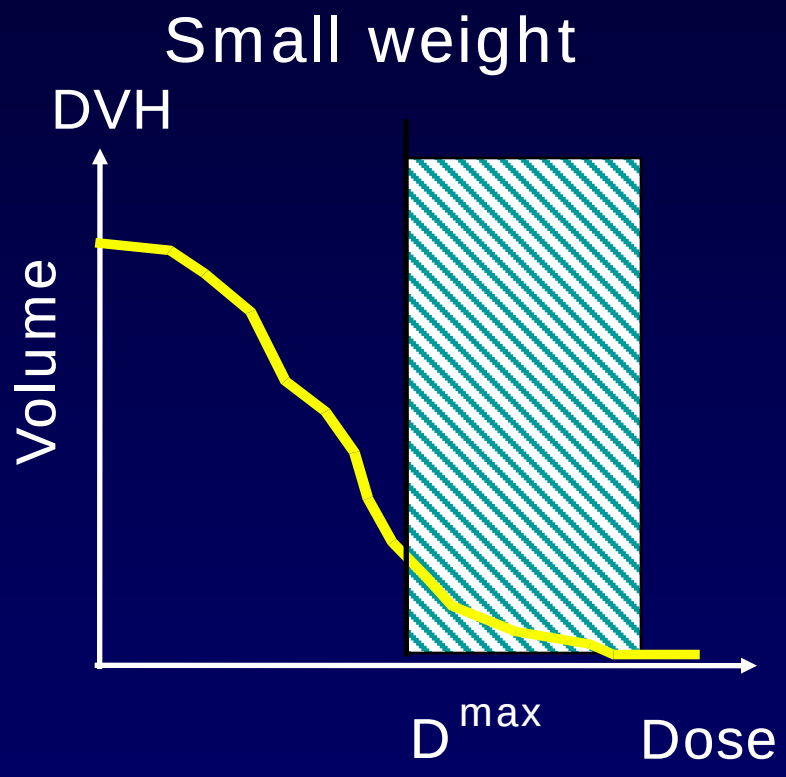
Target

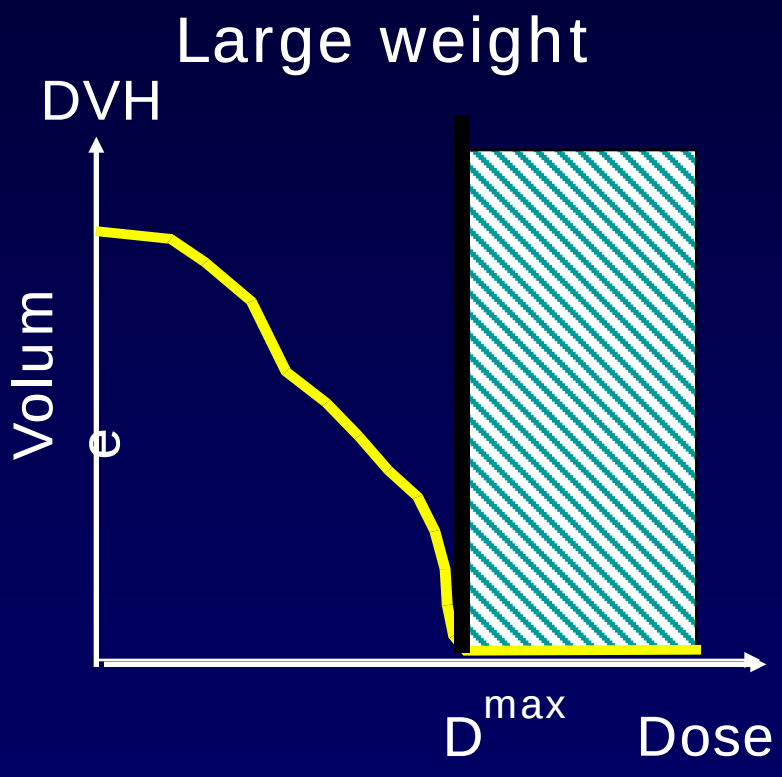


- Voxels below the specified minimum and above the specified maximum are penalized.

From Nucletron

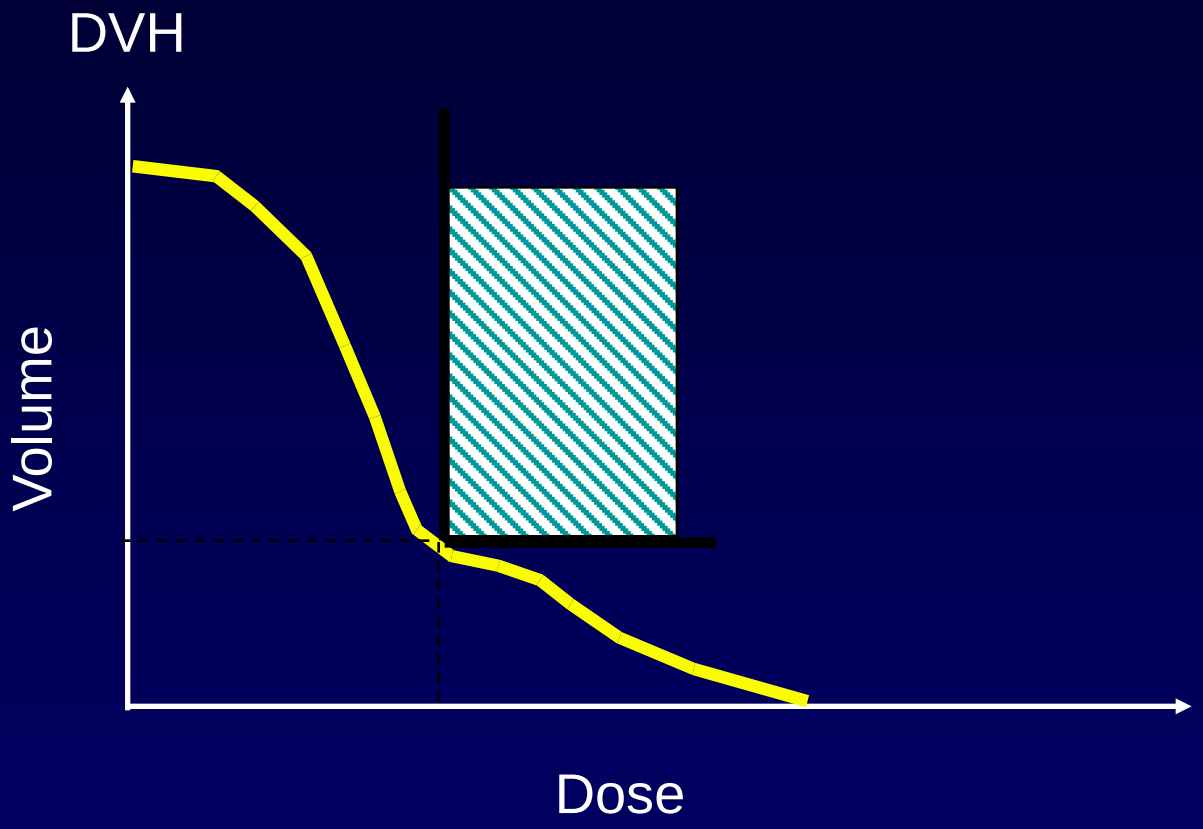
Sensitive Structures





From Nucletron

DVH Based Penalties



- A weighted penalty is applied if the DVH goal is not satisfied.

From Nucletron

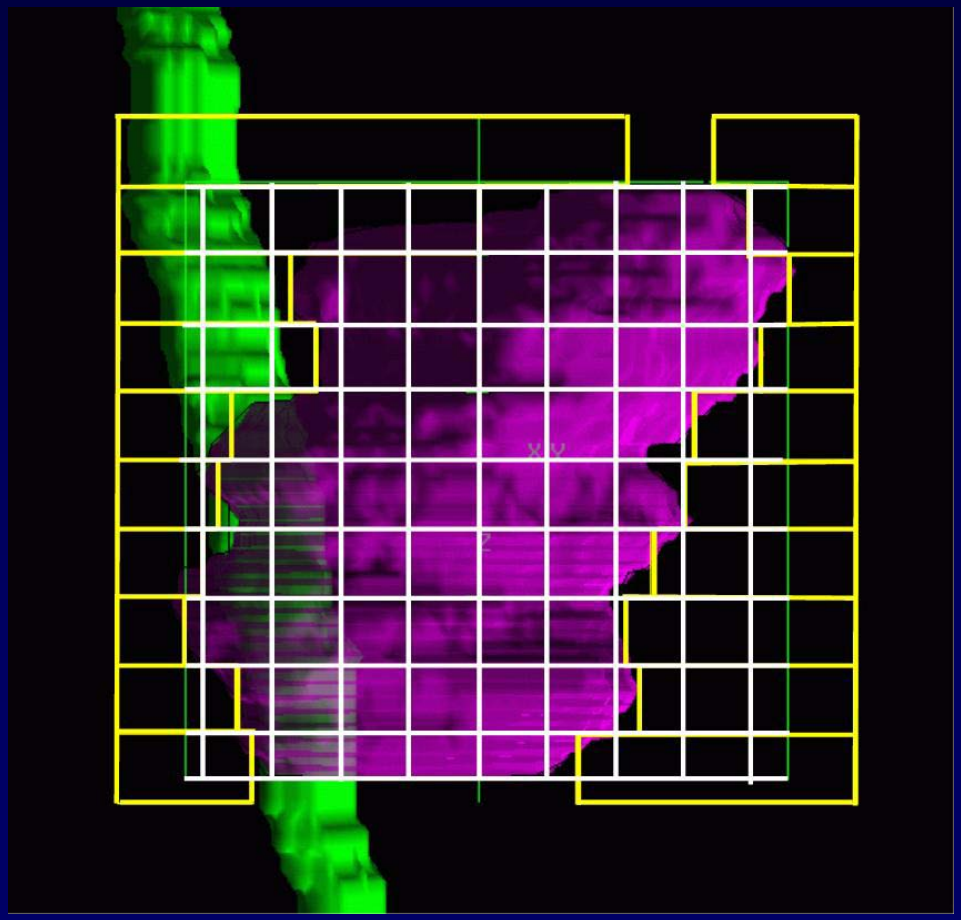
2. Plan Optimization

Plan Optimization
Fixed Field IMRT

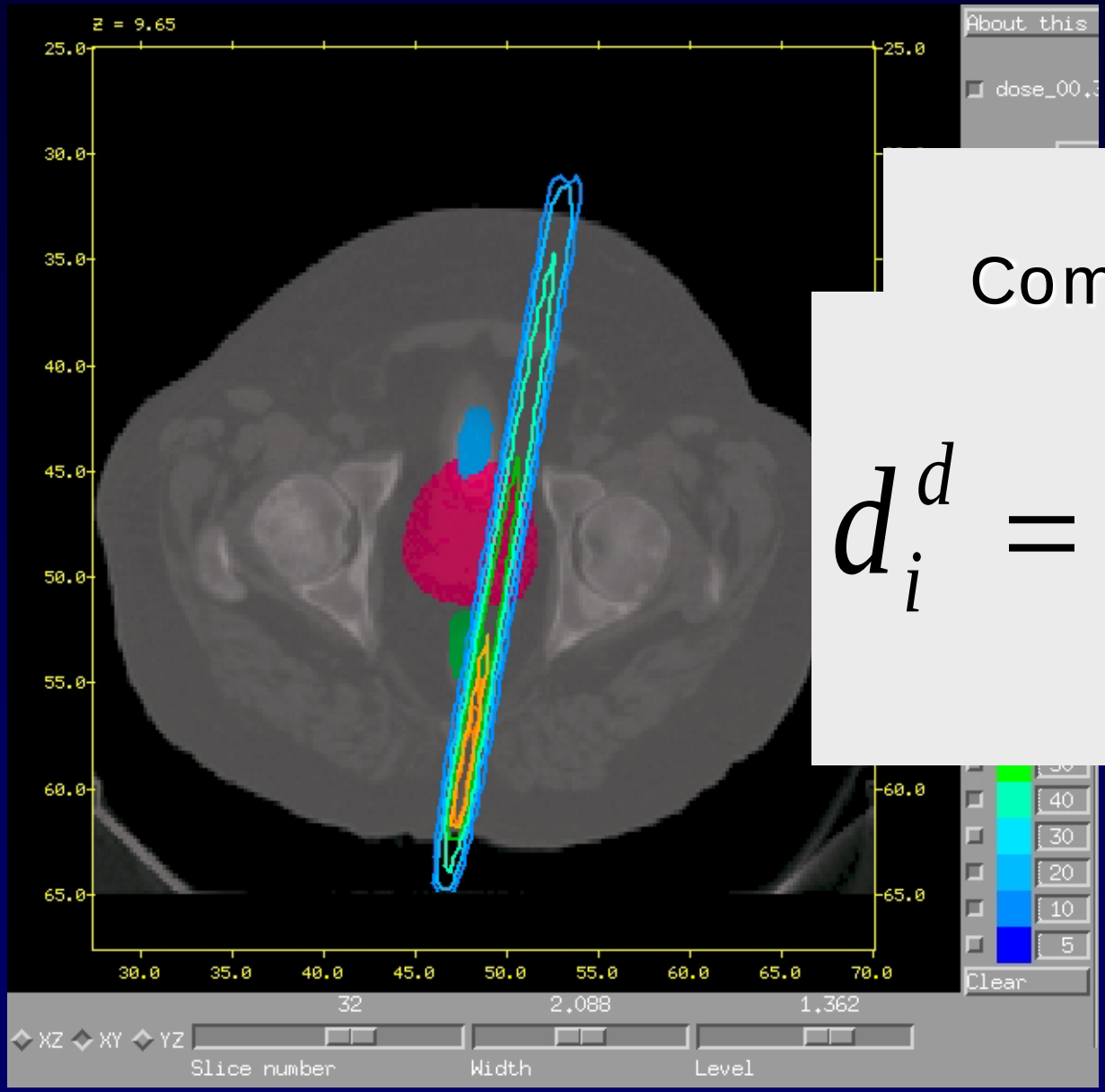
- Beamlet based optimization
- Direct aperture optimization

The Beamlet Model

Before an IMRT optimization, each beam is divided into a number of smaller beamlets (pencil beams), and the corresponding dose distributions are computed.



Beamlet Dose Distribution

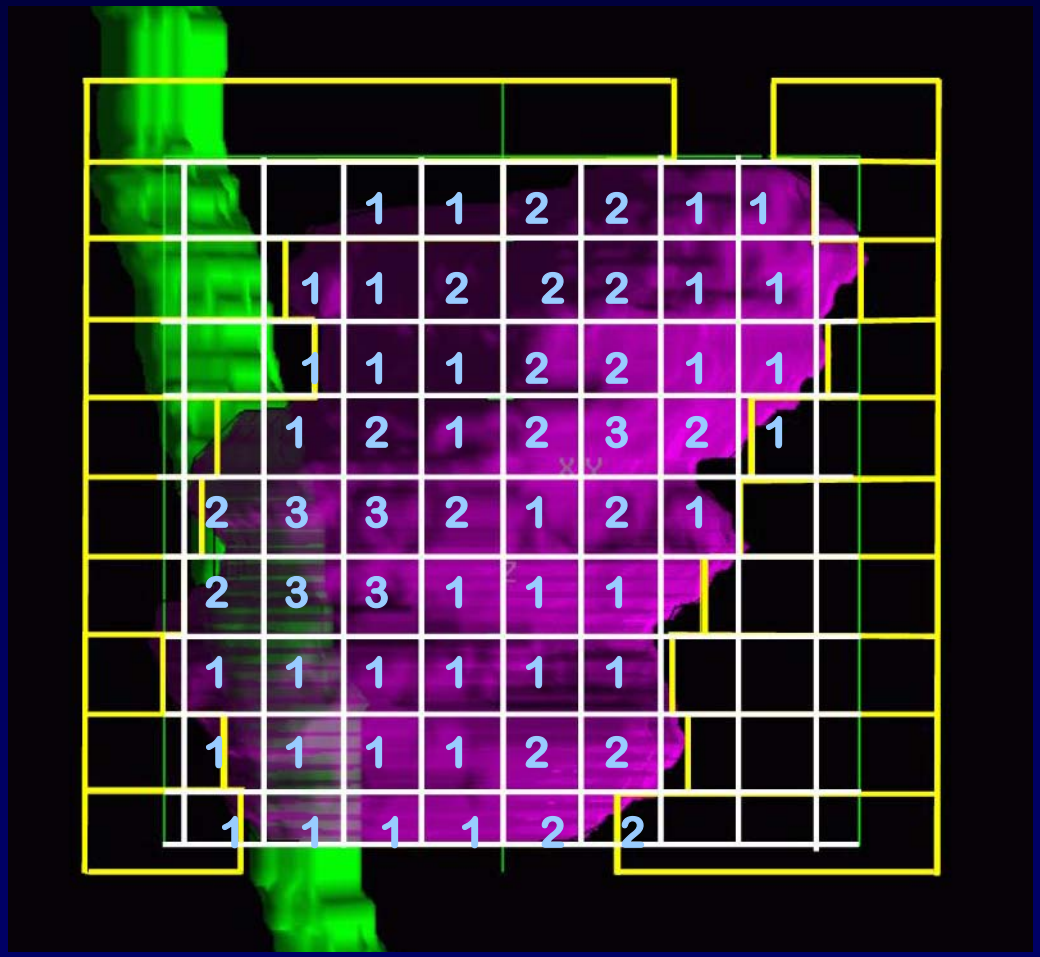


Dose Computation

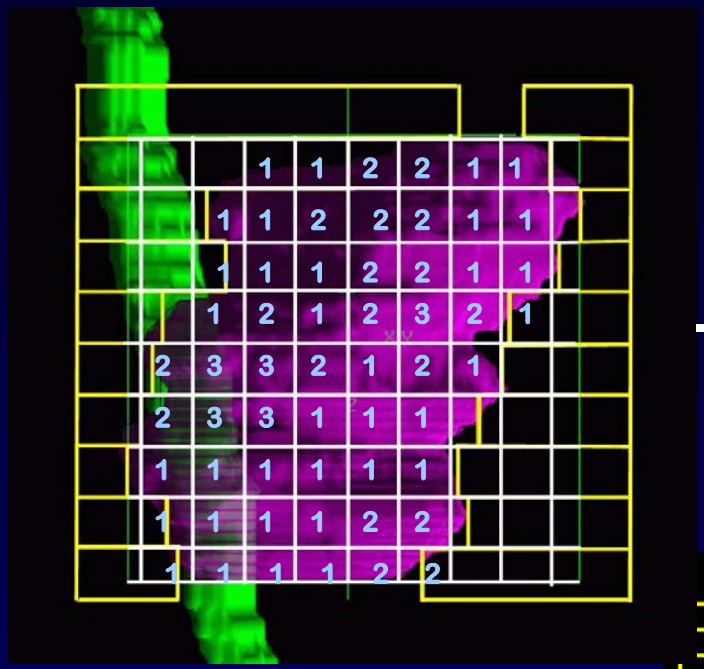
$$d_i^d = \sum_{j=1}^{n_p} D_{ij} w_j$$

Beamlet-Based Inverse Planning

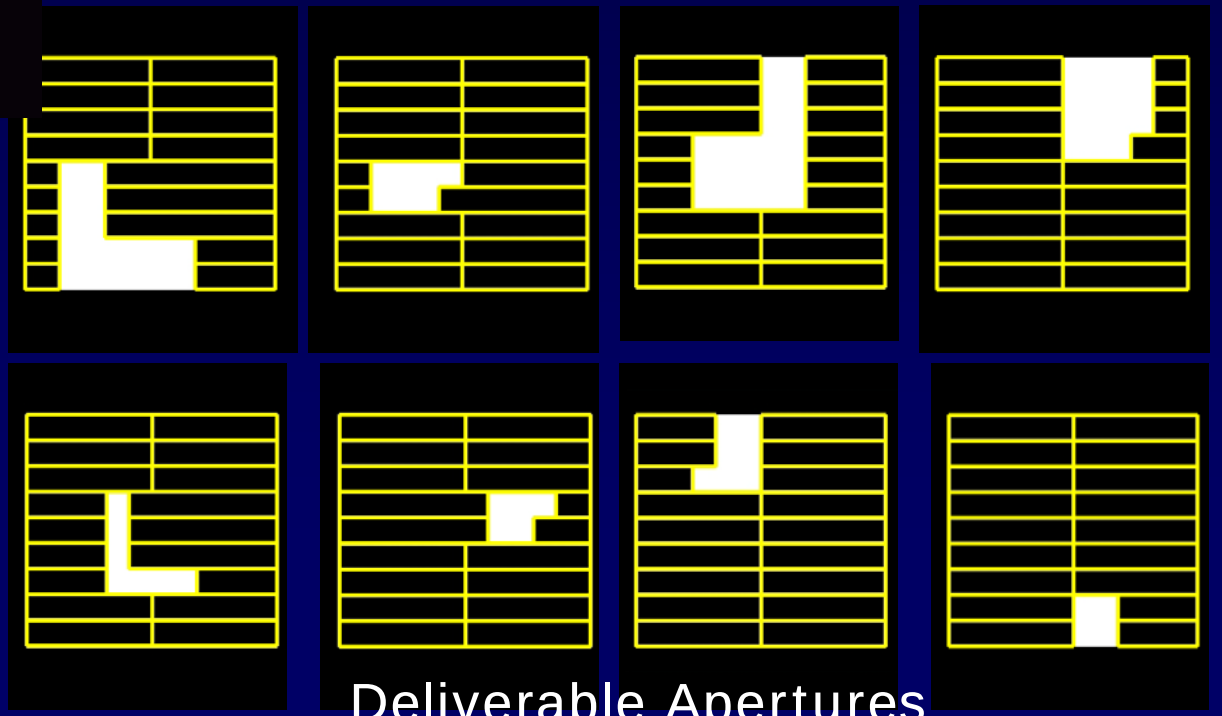
Beamlet weights are optimized to produce an optimized fluence map for each beam direction.



Optimized Fluence Map



Leaf Sequencing



Deliverable Apertures

From Optimized Intensity Map to Treatment
Leaf Sequencing

- The optimized treatment plan is not immediately ready for delivery.
- A leaf sequencing algorithm needs to be applied to translate the each optimized (theoretical) fluence map into a set of deliverable aperture shapes.
- The constraints imposed by the multileaf collimator are accounted for in the leaf sequencing step.

From Nucletron

Beamlet-Based Inverse Planning

- Two-step approach to treatment planning:
  1. Fluence map optimization
  2. Leaf sequencing – Accounts for delivery constraints of MLC
- Was employed by nearly all commercial vendors:
  - Corvus (NOMOS).
  - Pinnacle (ADAC).
  - Plato (Nucletron).
  - Xio (CMS)
  - Theraplan (MDS Nordion)

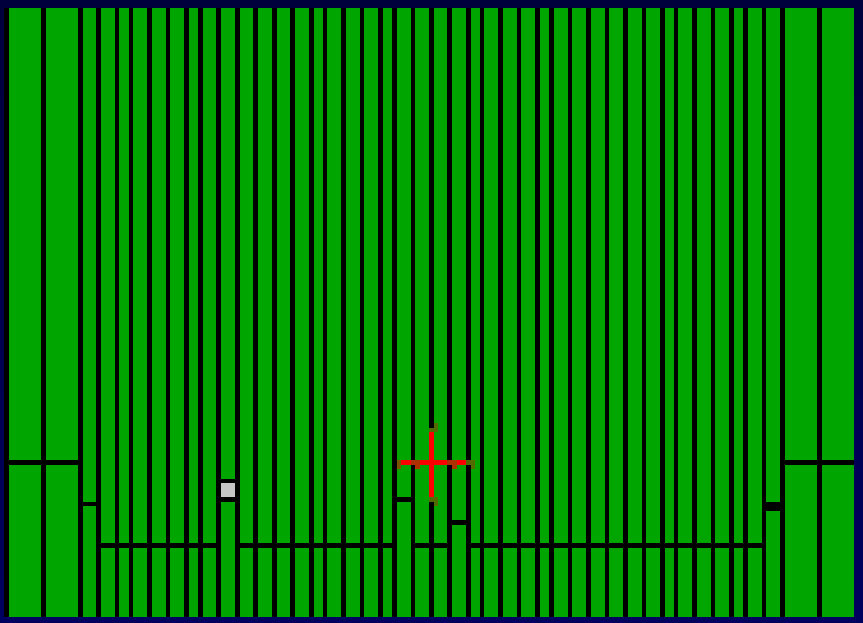
Deficiencies of Beamlet-based Inverse Planning

Step and Shoot IMRT

1. The plans require a large # of segments and a large # of monitor units. The leads to long treatment times.
2. There can be significant degradation in the plan quality as a result of the leaf sequencing process therefore making it difficult to create a final plan that meets all of the specified goals.

Beamlet-based Inverse Planning

Sliding Window



- Sliding window is MU inefficient but can delivery quickly due to the lack of intersegment delays.

Direct Aperture Optimization (DAO)

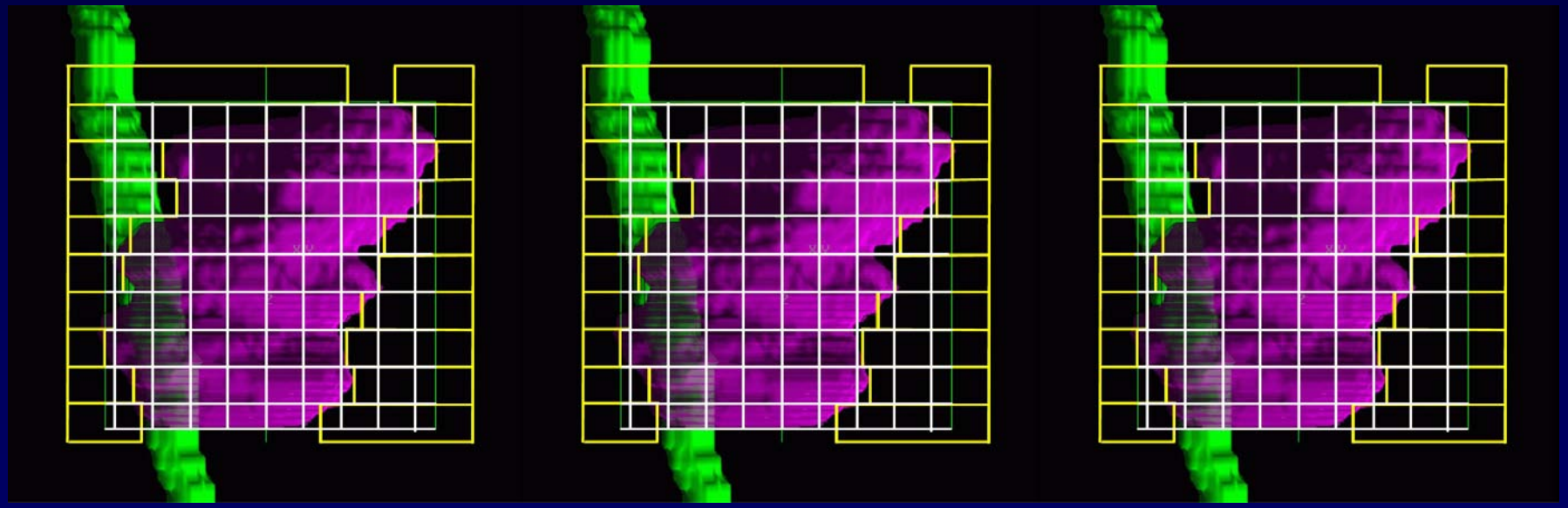
1. Inverse planning technique where the aperture shapes and weights are optimized simultaneously.
2. All of the MLC delivery constraints are included in the optimization
3. The number of aperture per beam angle is specified in the prescription.

DAO Optimization via Simulated Annealing

1) Pick a parameter (leaf position, aperture weight) randomly
2) Change the parameter by a random amount
3) Calculate objective function based on the new dose distribution
4) Objective function lower: accept change
5) Objective function higher: accept change with certain probability

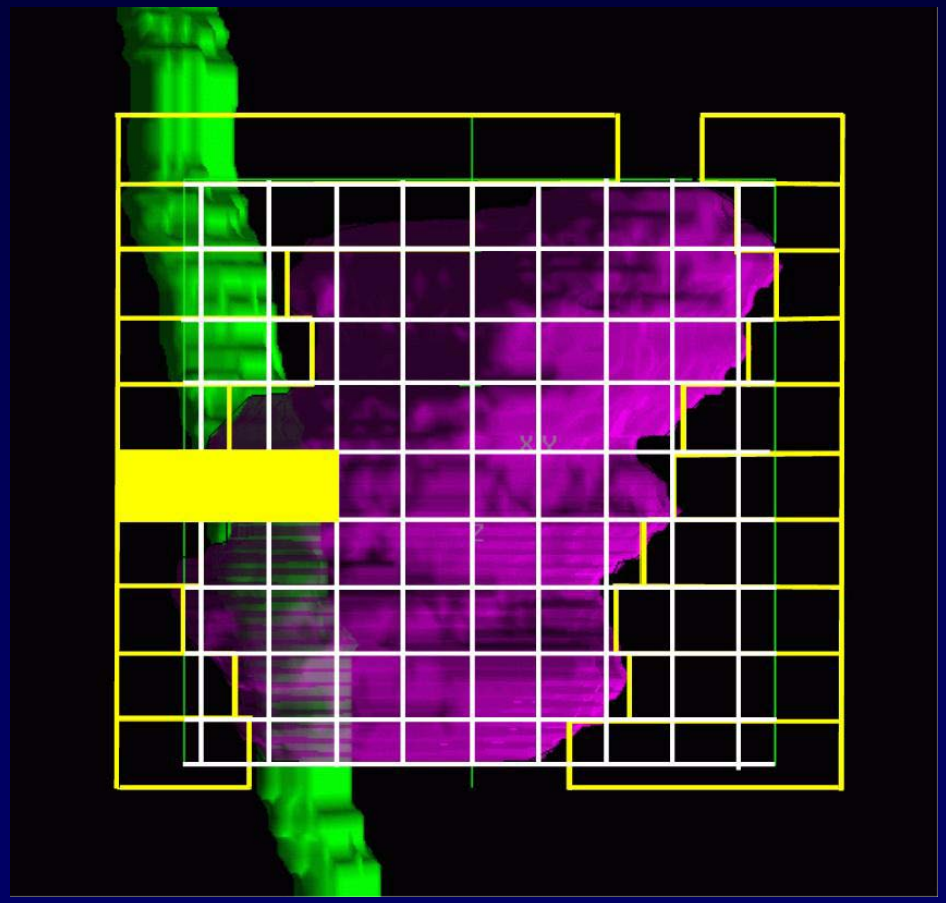
Prescription: 3 apertures per angle

Begin with 3 identical copies



Pick an Parameter and Make a Change

Aperture 1
Leaf pair 6
Left leaf position
Move leaf in 2cm



Keep or Reject the Change

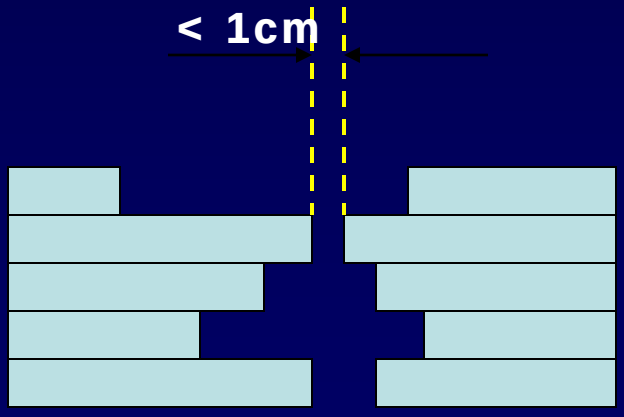
Based on:

1. MLC constraints.
2. Cost function & Annealing Rules.

MLC Constraints

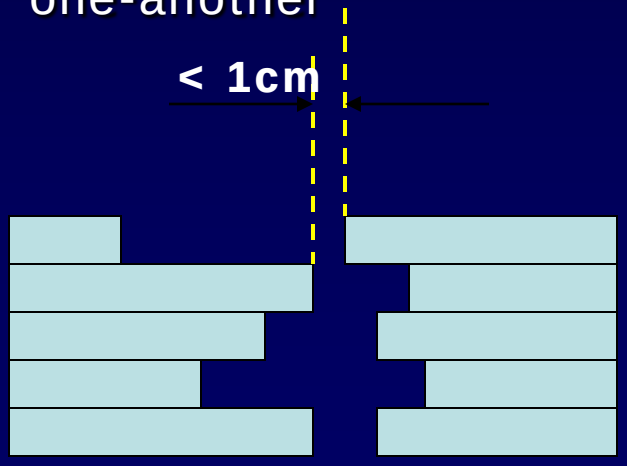
Some sample Elekta constraints:

1) Opposed leaves cannot come closer than 1-cm from one-another



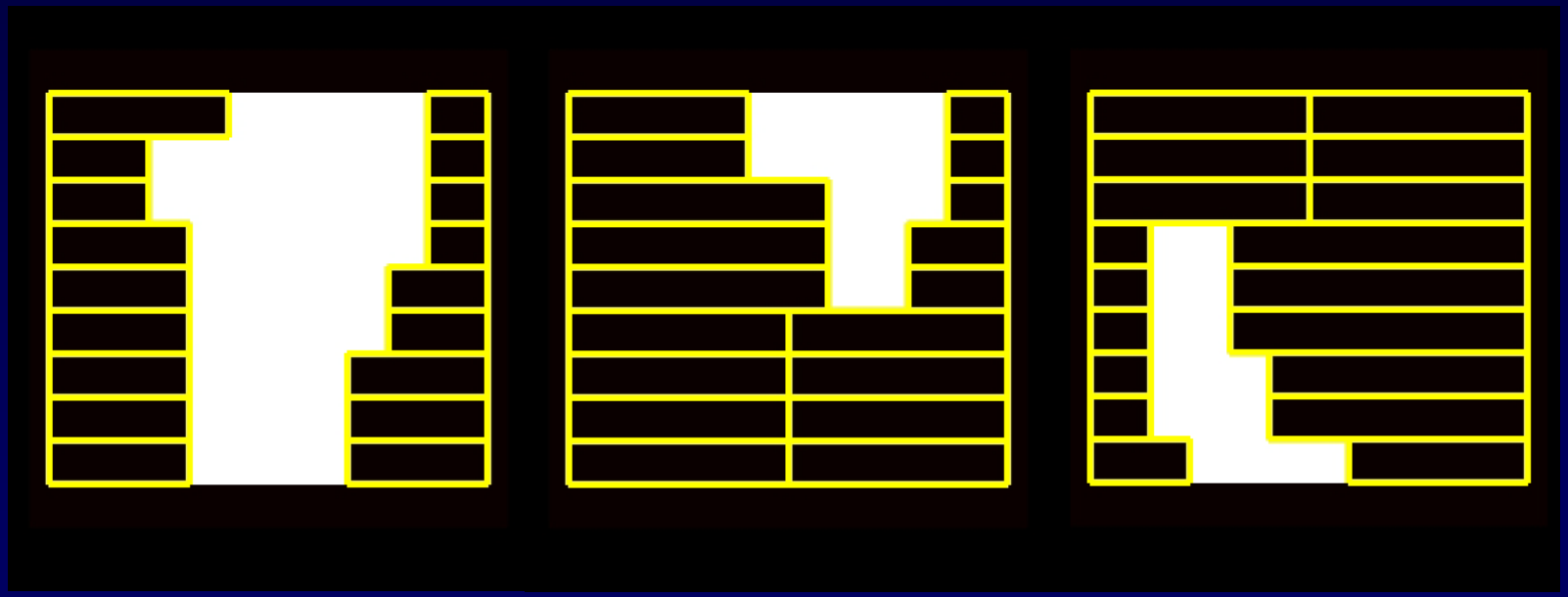
Not allowed

2) Opposed-adjacent leaves cannot come closer than 1-cm from one-another



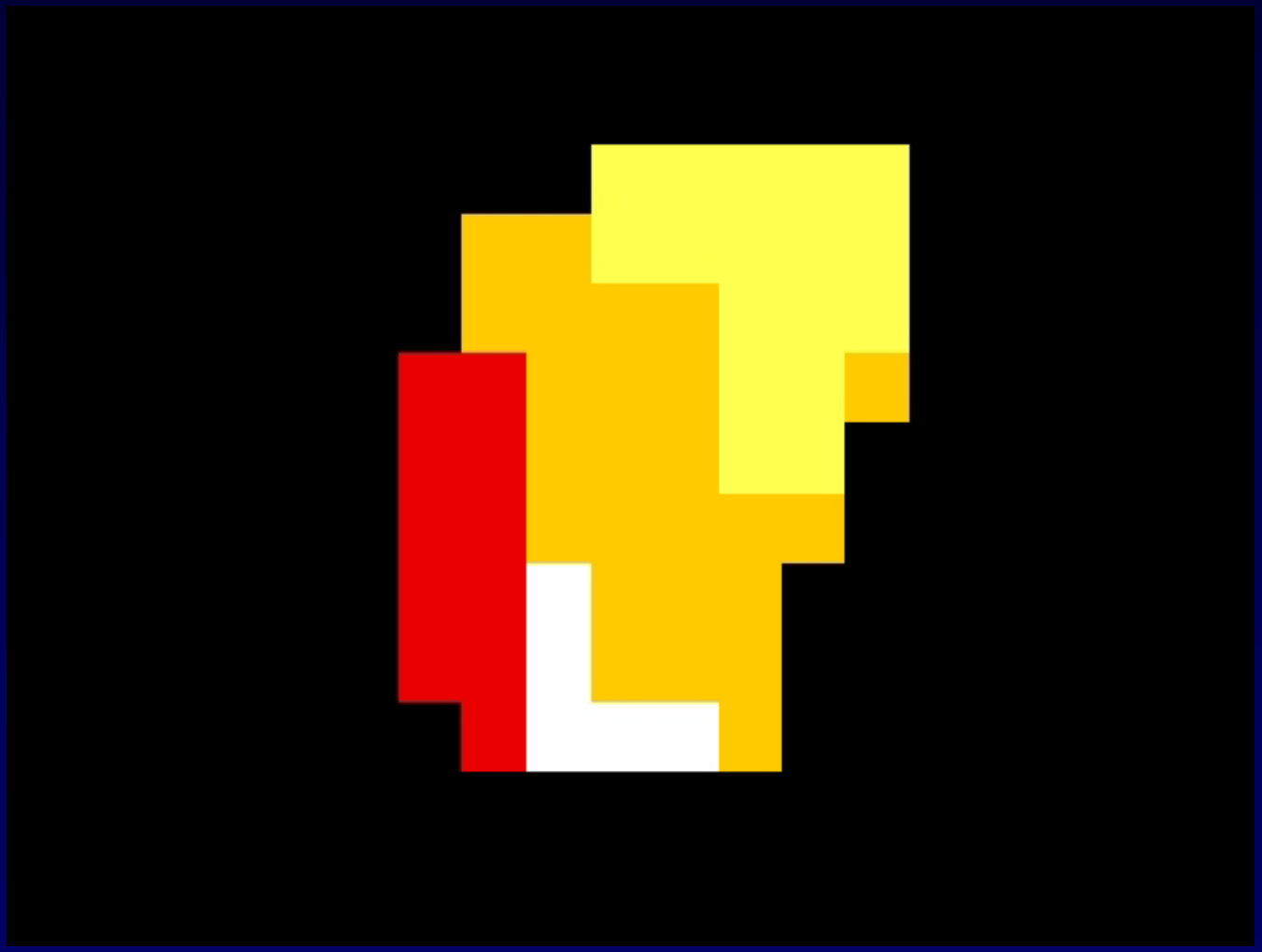
Not allowed

After numerous iterations...



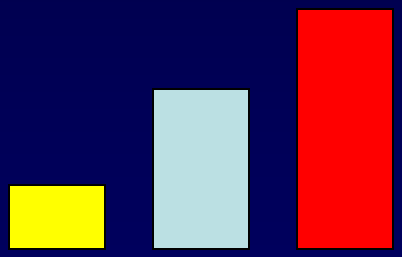
Add them up along with their weights…

Final intensity map from DAO

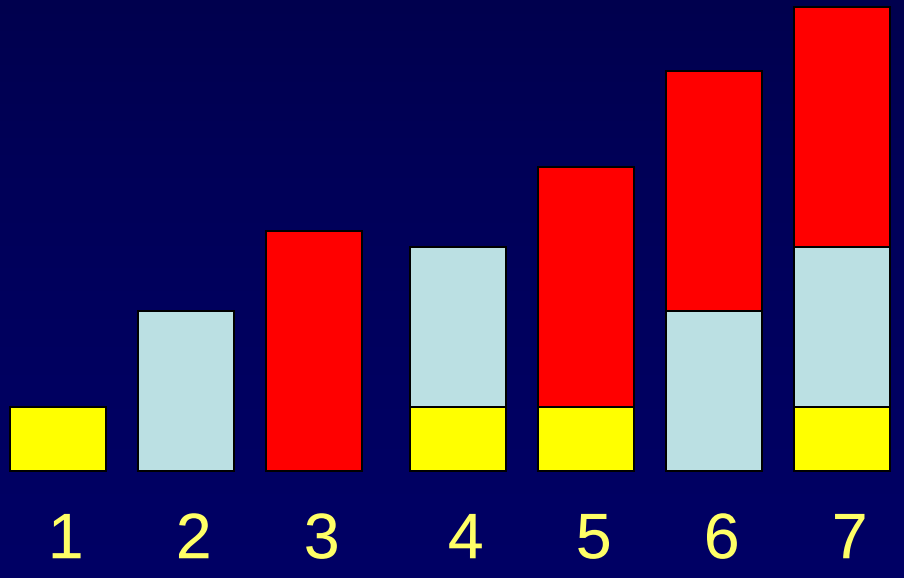


Small number of apertures can produce large number of intensity levels

Example: 3 apertures/angle



3 separate weights



Small number of apertures can produce large number of intensity levels

$$N_n = 2^n - 1$$

N = Number of intensity levels
n = Number of apertures

For 3 apertures, 7 intensities
For 4 apertures, 15 intensities
For 5 apertures, 31 intensities
For 6 apertures, 63 intensities

DAO - Benefits

1. Highly conformal IMRT plans with only 3 to 5 apertures per beam.
2. MU efficient and efficient delivery
3. Can be used for IMAT treatment planning.

4. Optimizing the fluence

Optimization Techniques

- Various optimization techniques have been employed to optimize fluence maps or aperture shapes in IMRT planning.
- IMRT plan optimization poses a very challenging optimization problem due to size of the problem and the inclusion of complex nonlinear functions such as DVH constraints.

Optimization Techniques

Deterministic

- Linear Programming
- Nonlinear Programming
- Mixed Integer Programming
- Iterative Techniques

Optimization Techniques

Stochastic

- Simulated Annealing
- Genetic Algorithms
- Tabu search.

Evaluating the Techniques

- Is it robust?
- Is it flexible?
- Is it fast?
- Do plans deliver efficiently?

IMAT Treatment Planning

IMAT Plan Optimization
Elekta VMAT/Varian Rapid Arc

- IMAT treatment planning represents a particularly complex optimization problem.
- This is due to: (1) the size of the problem and (2) the need to account for the interconnectedness of the beam shapes as the gantry rotates from one beam angle to the next.

First Generation IMAT
2000-2007

- Treatment plans were developed using forward planning or simple beam shaping based on the patient's anatomy.
- The dose rate was constant as the gantry rotated around the patient.

Next Generation IMAT
2008-

- Treatment plans with full inverse planning.
- The dose rate varies as the gantry rotates around the patient.

IMAT Inverse Planning Solutions

- Varian → Eclipse RapidArc
- Philips → Pinnacle SmartArc
- Elekta → Monaco VMAT
- Nucletron → Oncentra MasterPlan VMAT
- Siemens/Prowess → Prowess Panther

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INSTITUTE OF PHYSICS PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. **48** (2003) 1–15 PII: S0031-9155(03)57398-5

Inverse planning for intensity modulated arc therapy using direct aperture optimization

M A Earl, D M Shepard, S Naqvi, X A Li and C X Yu

Department of Radiation Oncology, University of Maryland School of Medicine, Baltimore, MD 21201, USA

DAO for IMAT

- The key feature of DAO is that all of the delivery constraints are included directly into the IMAT optimization.
- The optimizer starts by matching the shapes to the BEV of the target.
- Throughout the optimization the MLC leaf position are optimized but they are never allowed to violate the delivery constraints.

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IMAT Constraints

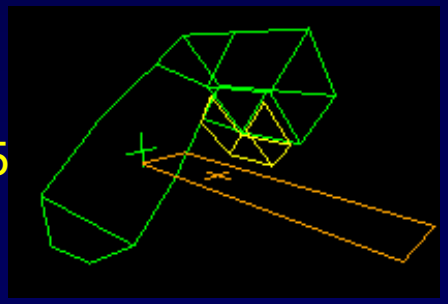
Leaves cannot change by a certain amount based upon

a) Maximum leaf travel speed

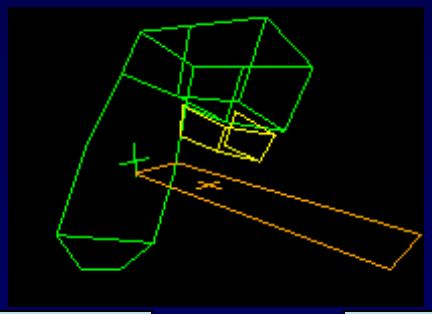
b) Gantry speed

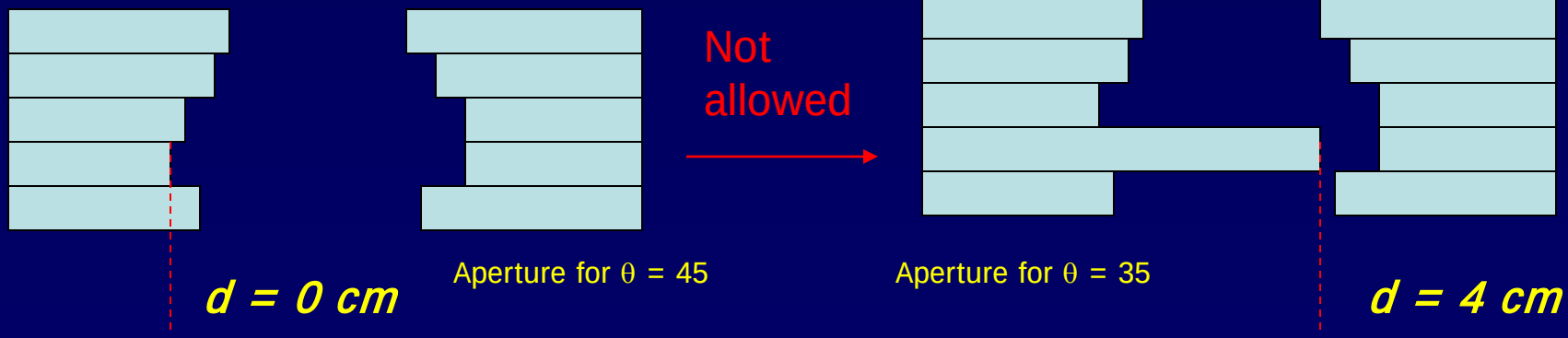
e.g. If gantry speed is 10 degrees/sec and leaf travel speed is 2 cm/sec, maximum leaf travel between two adjacent angles is 2-cm

θ = 45



θ = 35





Volumetric modulated arc therapy: IMRT in a single gantry arc

Karl Otto[a)]
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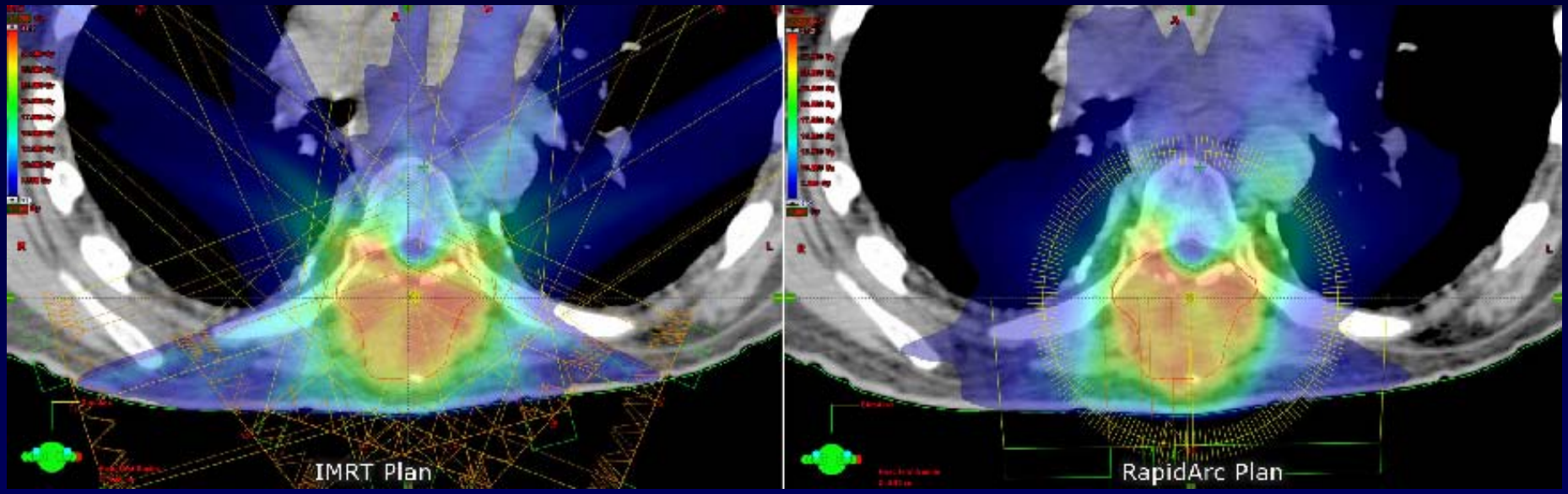
(Received 25 June 2007; revised 21 September 2007; accepted for publication 5 November 2007; published 26 December 2007)

In this work a novel plan optimization platform is presented where treatment is delivered efficiently and accurately in a single dynamically modulated arc. Improvements in patient care achieved through image-guided positioning and plan adaptation have resulted in an increase in overall treatment times. Intensity-modulated radiation therapy (IMRT) has also increased treatment time by requiring a larger number of beam directions, increased monitor units (MU), and, in the case of tomotherapy, a slice-by-slice delivery. In order to maintain a similar level of patient throughput it will be necessary to increase the efficiency of treatment delivery. The solution proposed here is a novel aperture-based algorithm for treatment plan optimization where dose is delivered during a single gantry arc of up to 360 deg. The technique is similar to tomotherapy in that a full 360 deg of beam directions are available for optimization but is fundamentally different in that the entire dose volume is delivered in a single source rotation. The new technique is referred to as volumetric modulated arc therapy (VMAT). Multileaf collimator (MLC) leaf motion and number of MU per

Eclipse VMAT

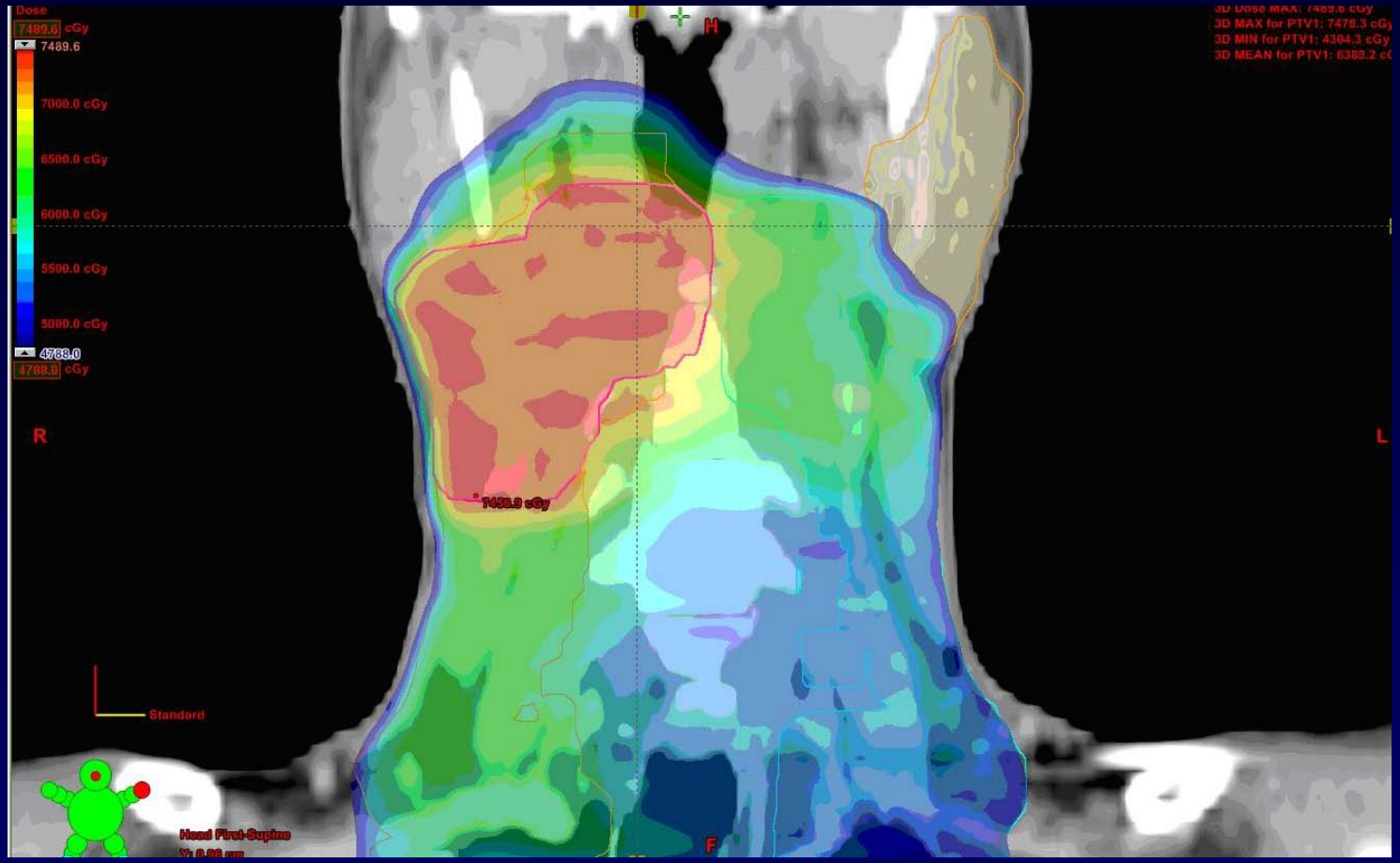
- In Otto's paper, he used DAO to produced IMAT plans.
- Two key innovations:
  1. Focused on a single arc approach with more control points in the single arc. Termed "VMAT".
  2. Progressive sampling was used to improve the speed of the algorithm.
- This is the approach utilized in Eclipse

Varian Eclipse



- Planning is performed using Direct Aperture Optimization.
- Typical plan uses 1 arc with 177 control points.
- For some cases, multiple arcs are use to improve the plan quality or provide adequate coverage of large targets.

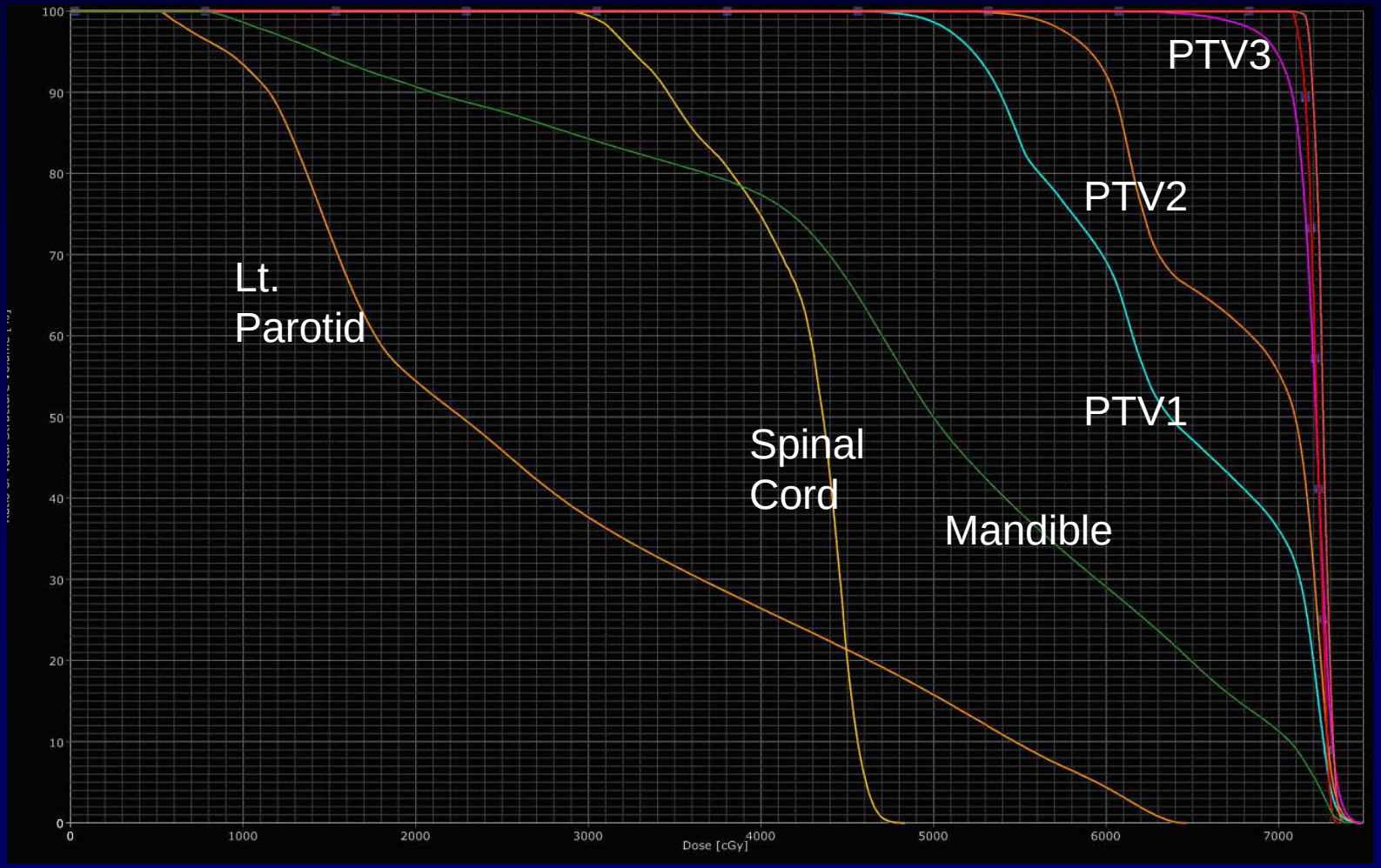
Varian Eclipse



- Composite dose for H&N patient treated at UMMS.
- Initial = 50.4 Gy, SFB1 = 9Gy, SFB2=10.8Gy

Courtesy of Warren D'Souza

Varian Eclipse



- Initial plan and SFB1 used 2 arcs, SFB2 used 1 arc
- Delivery time = 1.5 minutes per arc

Courtesy of Warren D'Souza

Philips Pinnacle – SmartArc

Planning Steps

1. Add a dynamic arc beam
2. Specify couch, collimator, and beam angles
3. Specify dose objectives
4. Specify SmartArc optimization parameters
5. Optimize
6. Compute final convolution dose

SWEDISH

Courtesy Kevin Reynolds

SmartArc Optimization (1)

1. Beams are generated at the start and the stop angles and at 24° increments from the start angle.
2. A fluence map optimization is performed.
3. The fluence maps are sequenced and filtered so that there are only 2 control points per initial beam angle.

Courtesy of Philips Medical

SmartArc Optimization (2)

4. These control points are distributed to adjacent gantry angles and additional control points are added to achieve the desired final gantry spacing.
5. All control points are processed to comply with the motion constraints of VMAT.

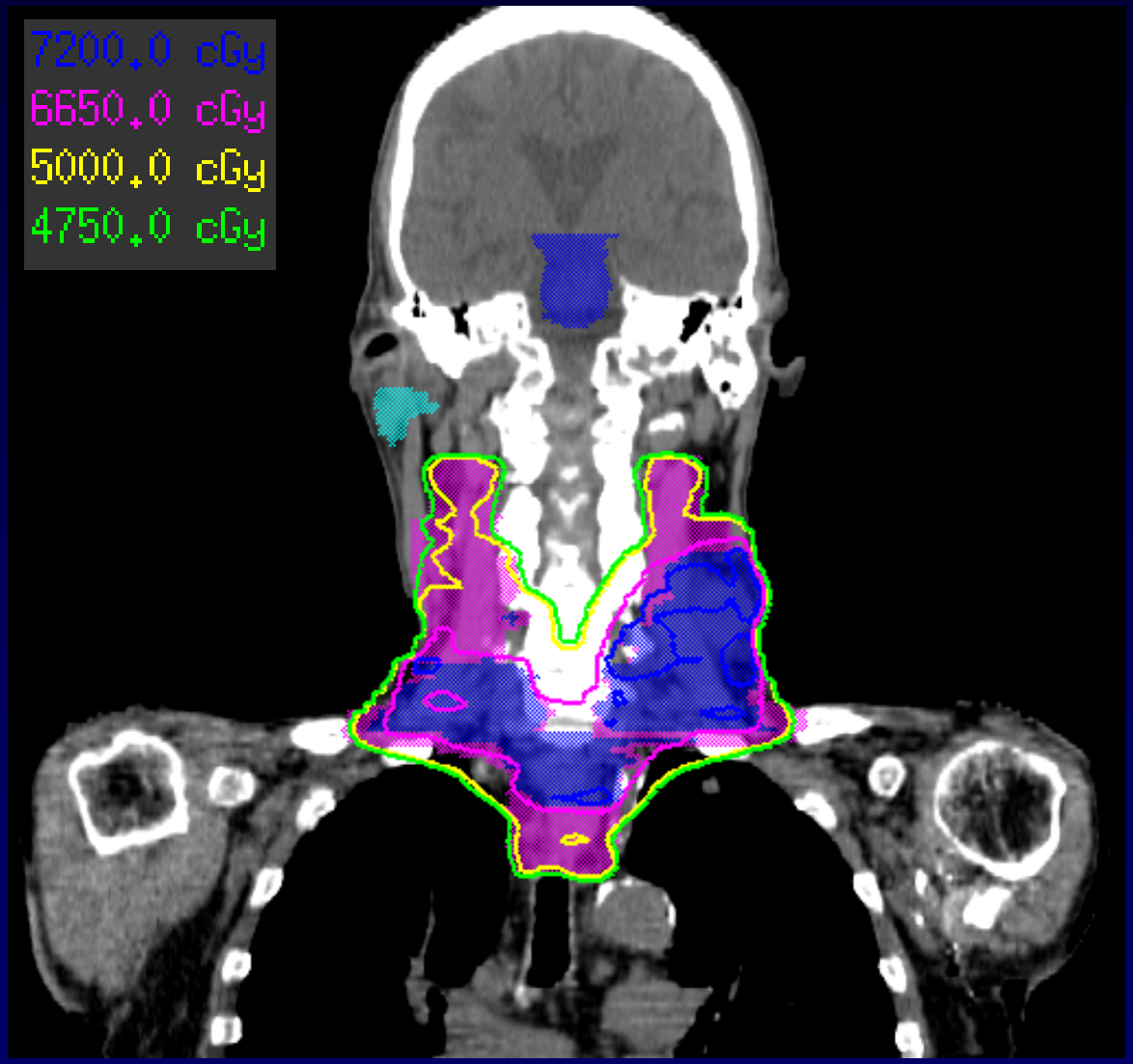
Courtesy of Philips Medical

SmartArc Optimization (3)

6. The DMPO algorithm is applied with an aperture based optimization that takes into account all of the VMAT delivery constraints.
7. The jaws are conformed to the segments based on the characteristics of the linac.

Courtesy of Philips Medical

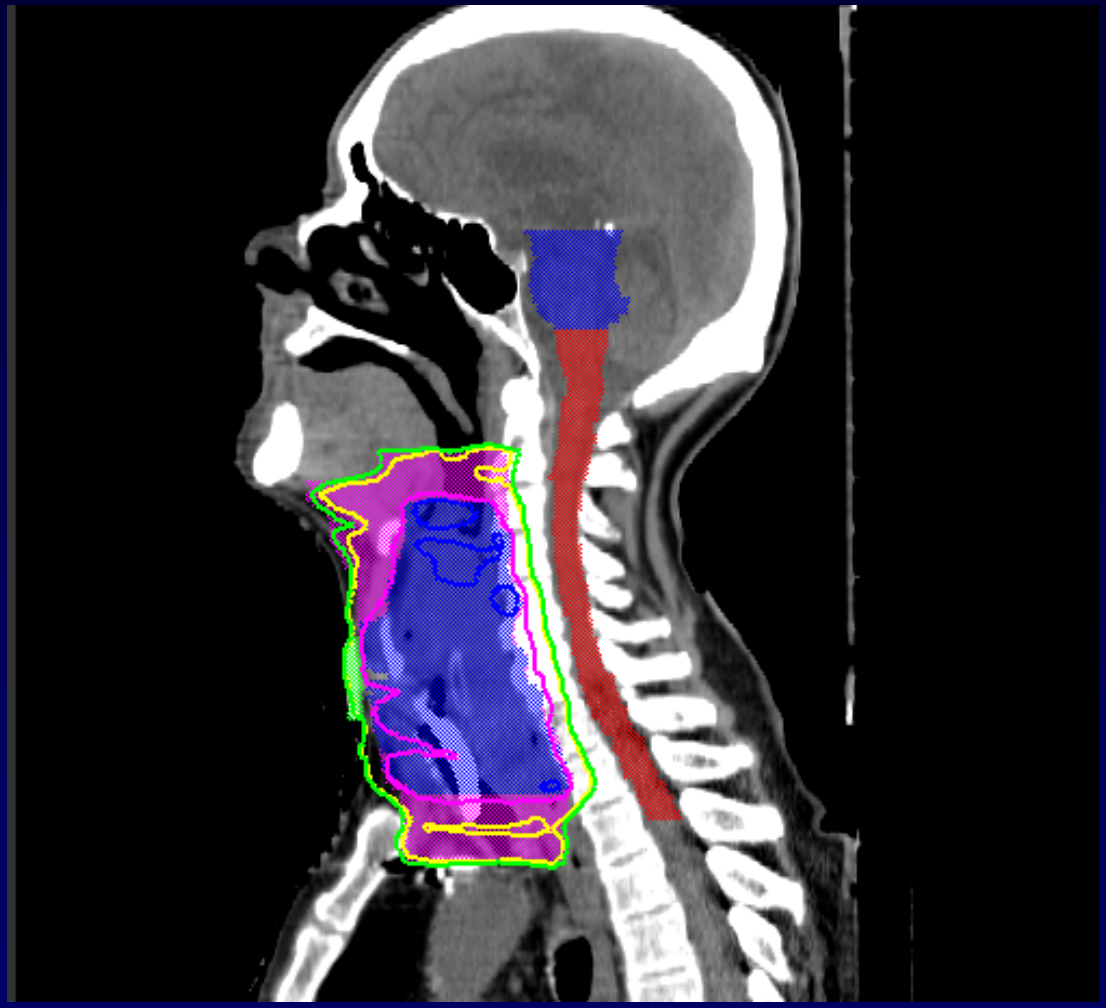
H&N – Treated with SmartArc



- 2 arc H&N delivery

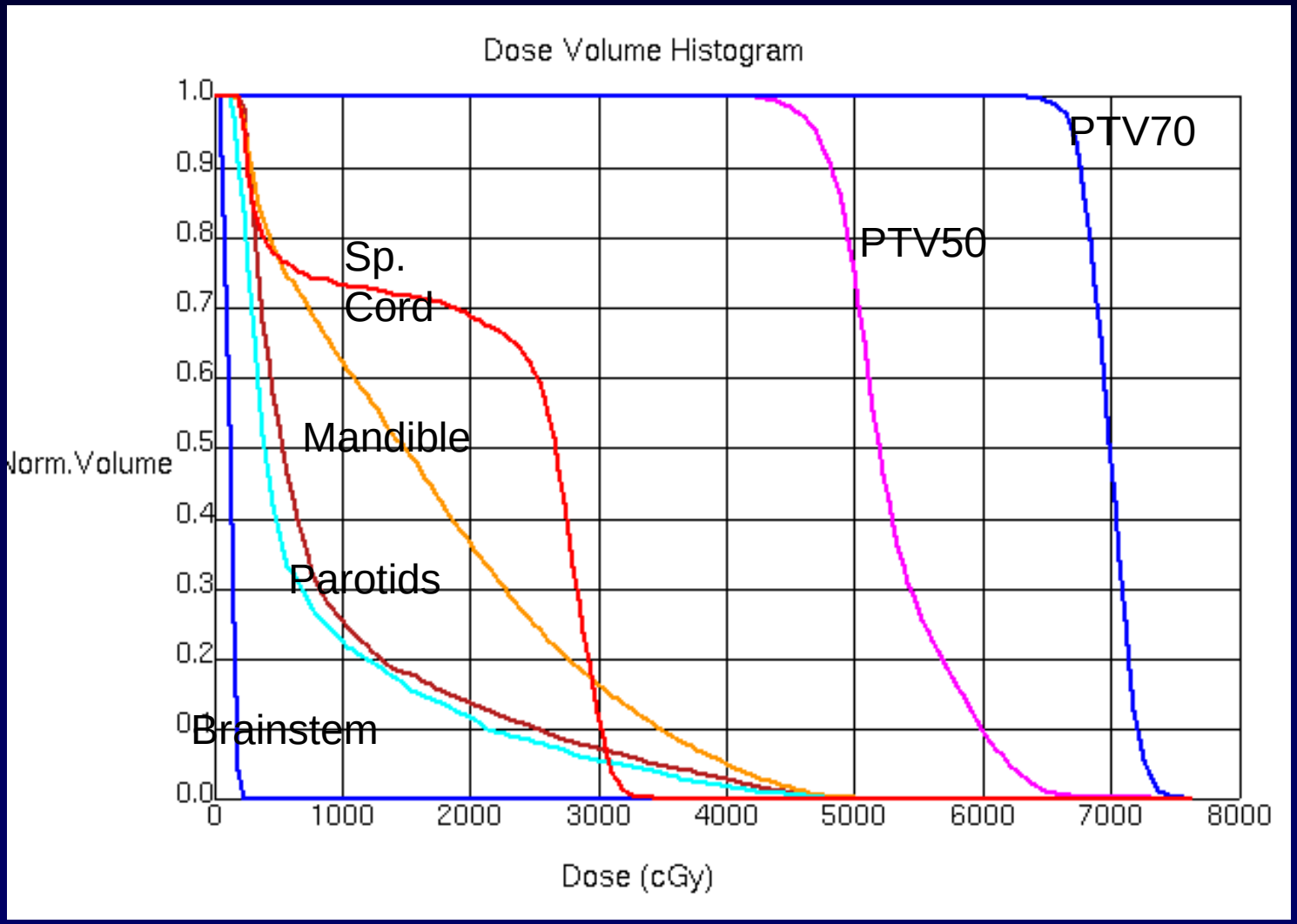
SWEDISH

H&N – Treated with SmartArc



SWEDISH

H&N – Treated with SmartArc



Plan Optimization
Tomotherapy (1)

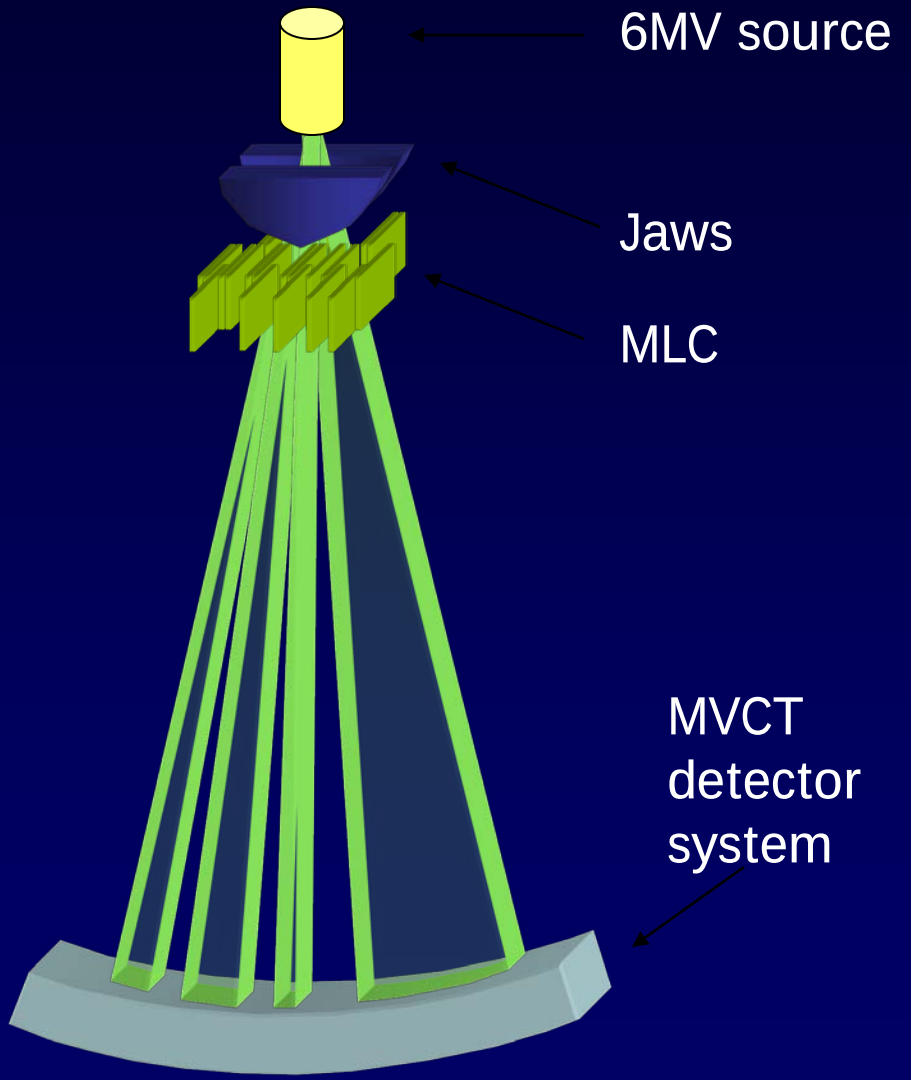
- The rotational nature of tomotherapy combined with the binary MLC means that typical plans include tens of thousands of beamlets.
- This give great flexibility in shaping the dose distribution but makes this is very data intensive optimization problem.

Plan Optimization
Tomotherapy (2)

- Tomotherapy planning requires the selection of parameters such as the pitch, field width, and modulation.

Field Width

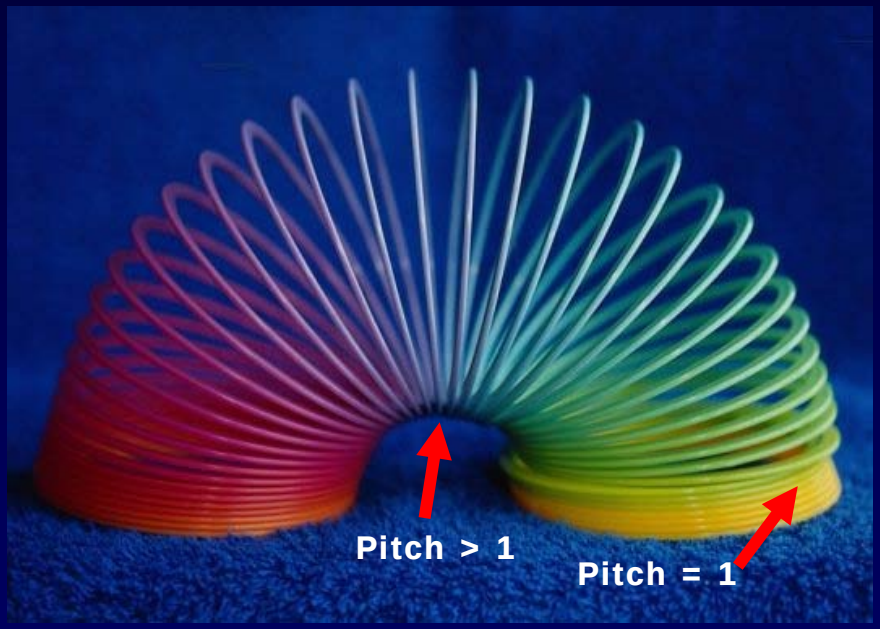
- Jaws define the field size along the *y*-axis: 1.05, 2.50, or 5.02 cm FWHM at iso.



Pitch

$$pitch = \frac{d_{couch} / rotation}{field\ width}$$

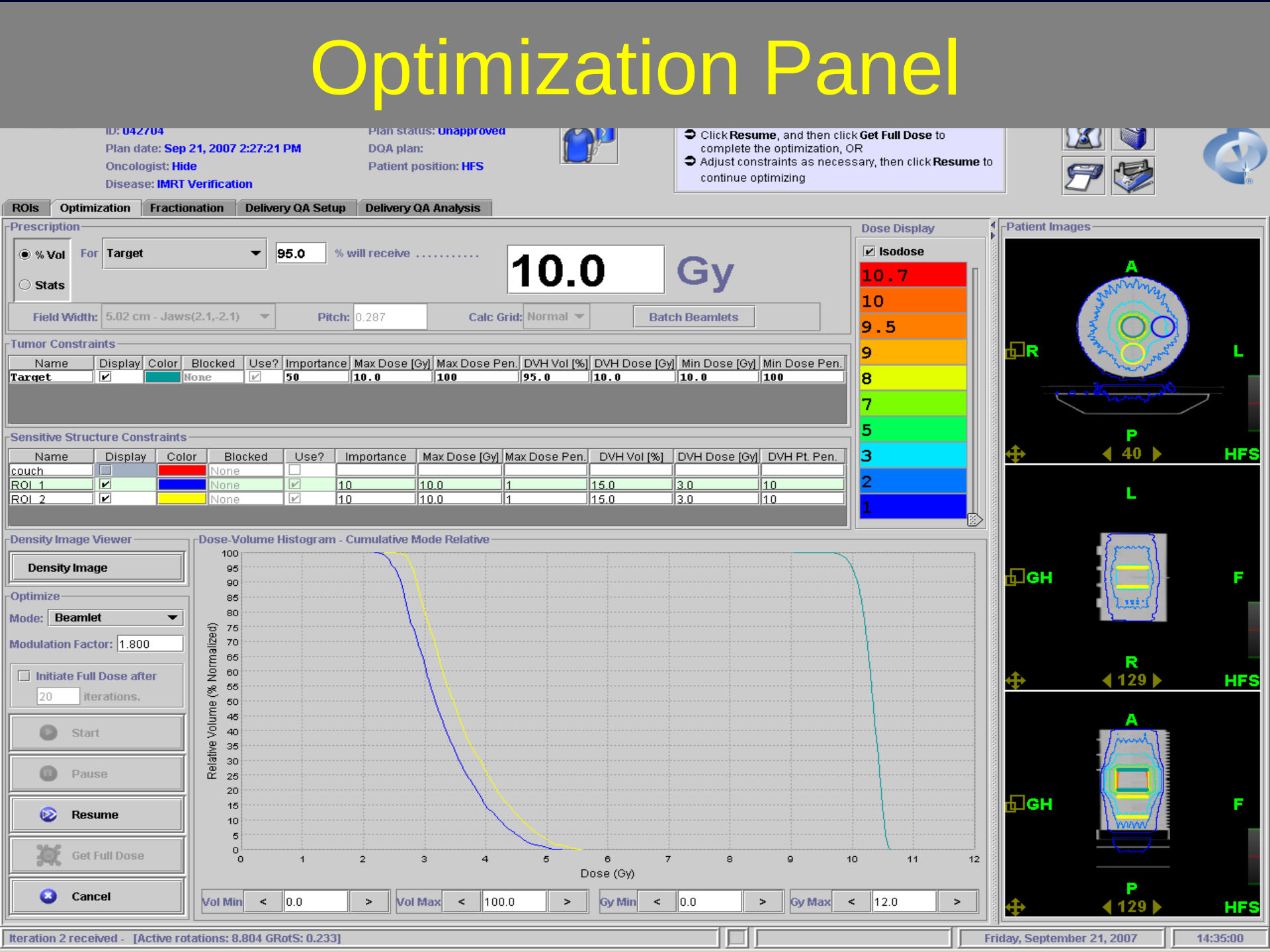
- Pitch < 1: Overlap from one rotation to the next (more tightly wound helix).



Modulation Factor (MF)

- The modulation factor limits the range of allowable leaf open times.
- This give the user a key tool striking the optimal balance between conformality and efficiency.

Optimization Panel



4. Future Developments: Multicriteria Optimization

-----Original Message-----

From: Cornell, Mariel J.
Sent: Friday, October 26, 2007 8:21 AM
To: Hong, Theodore S.,M.D.
Subject: C***

Hi,
I played around with Ms C***'s plan all day yesterday, but even with relaxing the Rt Kidney restraints, the liver and stomach doses don't budge. If I push it, the PTV and CTV coverage really suffers. Are you willing to sacrifice their coverage or would you prefer to go with the plan you reviewed the other day? She's coming this afternoon for VSim.

Thanks,
Mariel

Courtesy of Thomas Bortfeld

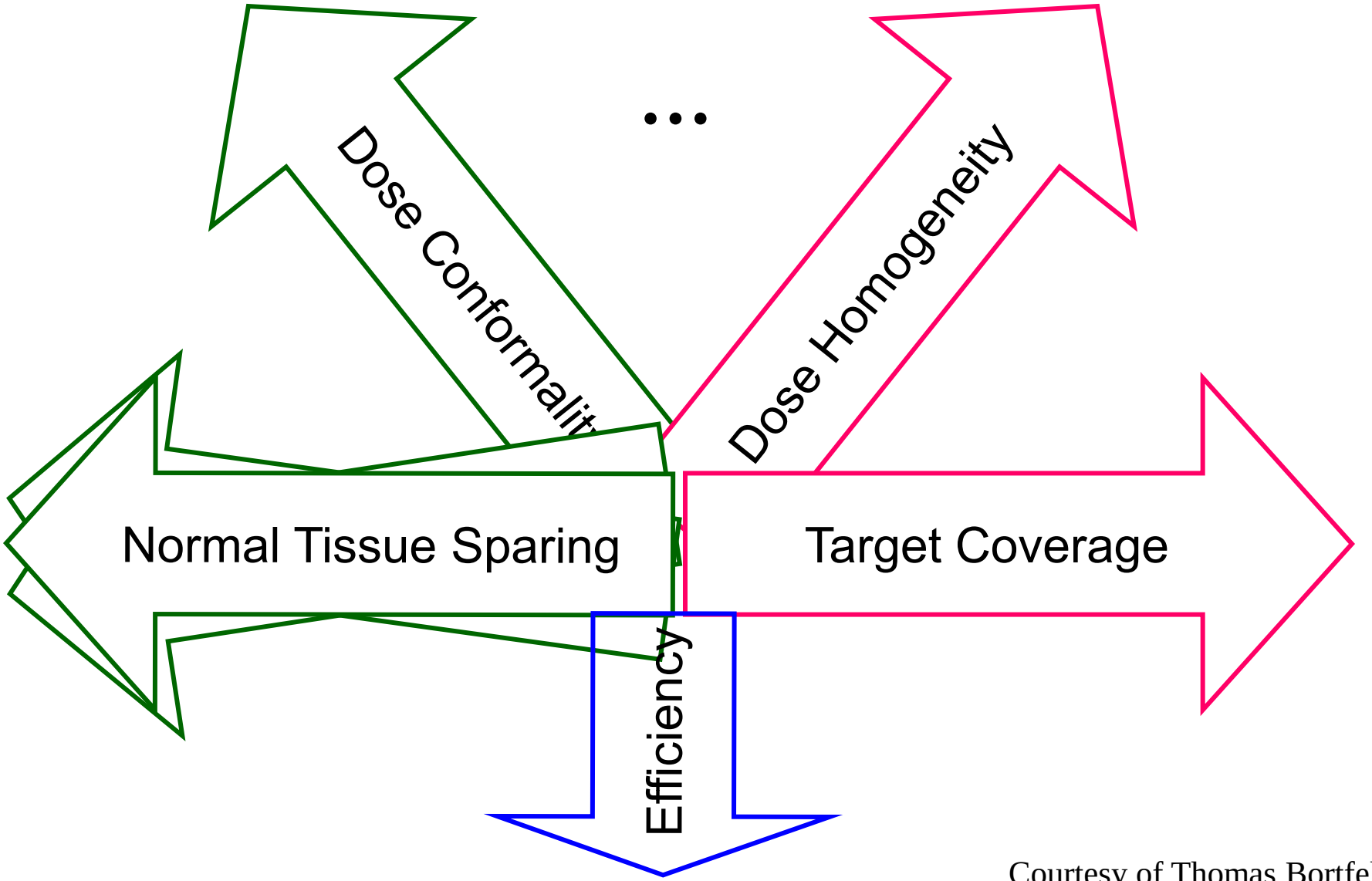
Human Iteration Loop

- Dose prescription , weight factors, …
- Optimization
- Plan evaluation

5 – 10 times

Courtesy of Thomas Bortfeld

Treatment planning has *multiple* objectives



Courtesy of Thomas Bortfeld

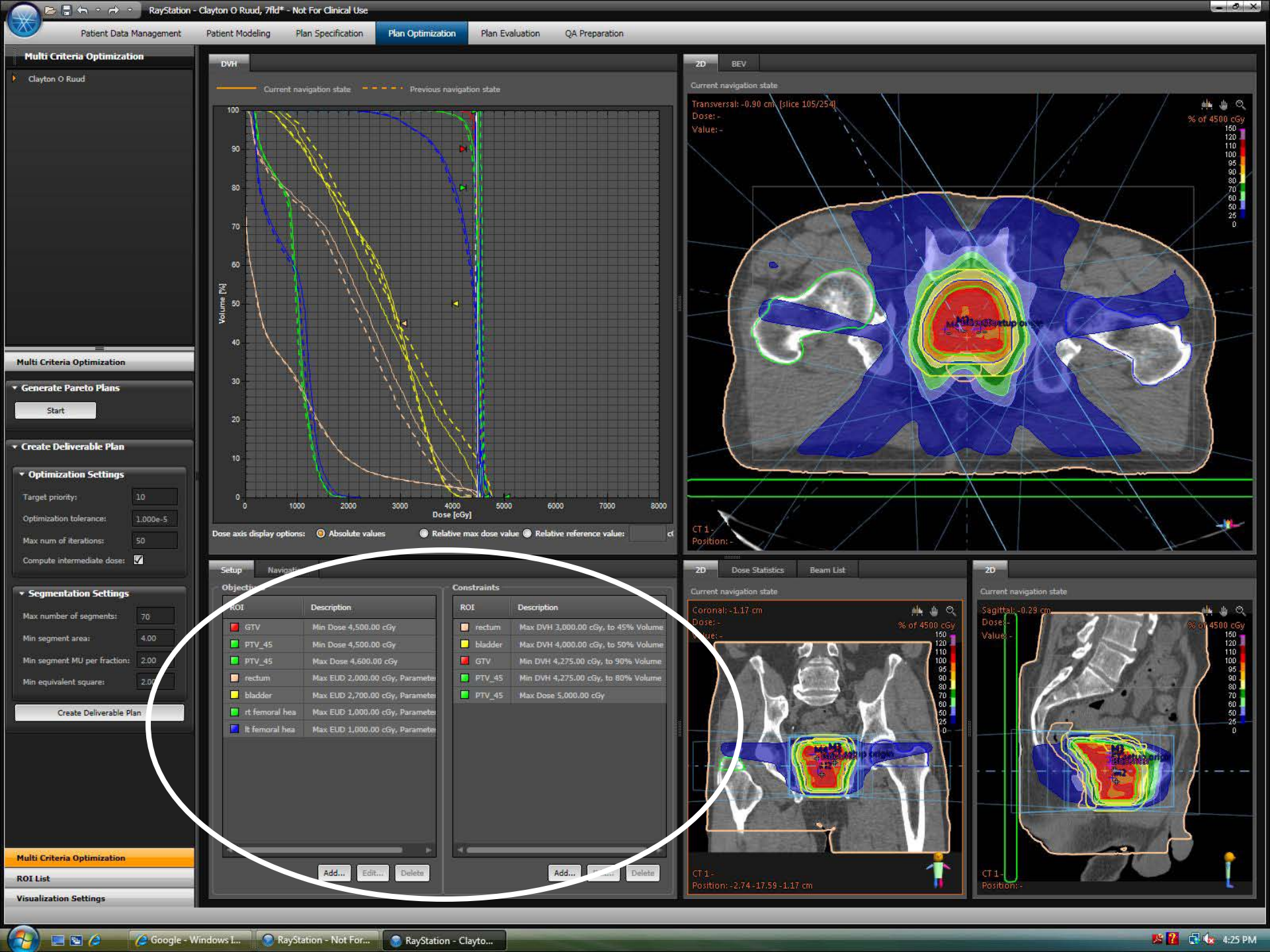
Pareto Optimization

- Pareto efficient situations are those in which it is impossible to make one person better off without necessarily making someone else worse off.
- A treatment plan is Pareto optimal if there is no other treatment plan that is at least as good in all objective functions and strictly better in one objective function value.

Multicriteria Optimization (MCO)

- A series of Pareto optimized solutions are produced.
- An interactive plan navigation tool can then be employed explore the optimal tradeoff between the planning goals for the patient.
- This can be done in minutes (as opposed to hours or days for the conventional method)

SWEDISH


RayStation - Clayton O Ruud, 7fld* - Not For Clinical Use
Patient Data Management
Patient Modeling
Plan Specification
Plan Optimization
Plan Evaluation
QA Preparation
Multi Criteria Optimization
Clayton O Ruud
DVH
Current navigation state
Previous navigation state
Volume [%]
Dose [cGy]
Dose axis display options:
Absolute values
Relative max dose value
Relative reference value:
2D
BEV
Current navigation state
Transversal: -0.90 cm [slice 105/254]
Dose: -
Value: -
% of 4500 cGy
CT 1 -
Position: -
Multi Criteria Optimization
Generate Pareto Plans
Start
Create Deliverable Plan
Optimization Settings
Target priority:
Optimization tolerance:
Max num of iterations:
Compute intermediate dose:
Segmentation Settings
Max number of segments:
Min segment area:
Min segment MU per fraction:
Min equivalent square:
Create Deliverable Plan
Setup
Objectives
Constraints
ROI
Description
GTV
Min Dose 4,500.00 cGy
PTV_45
Min Dose 4,500.00 cGy
Max Dose 4,600.00 cGy
rectum
Max EUD 2,000.00 cGy, Parameter
bladder
Max EUD 2,700.00 cGy, Parameter
rt femoral hea
Max EUD 1,000.00 cGy, Parameter
lt femoral hea
Max EUD 1,000.00 cGy, Parameter
Max DVH 3,000.00 cGy, to 45% Volume
Max DVH 4,000.00 cGy, to 50% Volume
Min DVH 4,275.00 cGy, to 90% Volume
Min DVH 4,275.00 cGy, to 80% Volume
Max Dose 5,000.00 cGy
Add...
Edit...
Delete
Dose Statistics
Beam List
Coronal: -1.17 cm
Position: -2.74 -17.59 -1.17 cm
Sagittal: -0.29 cm
Multi Criteria Optimization
ROI List
Visualization Settings
Google - Windows I...
RayStation - Not For...
RayStation - Clayto...
4:25 PM

Setup | Navigation

Objectives

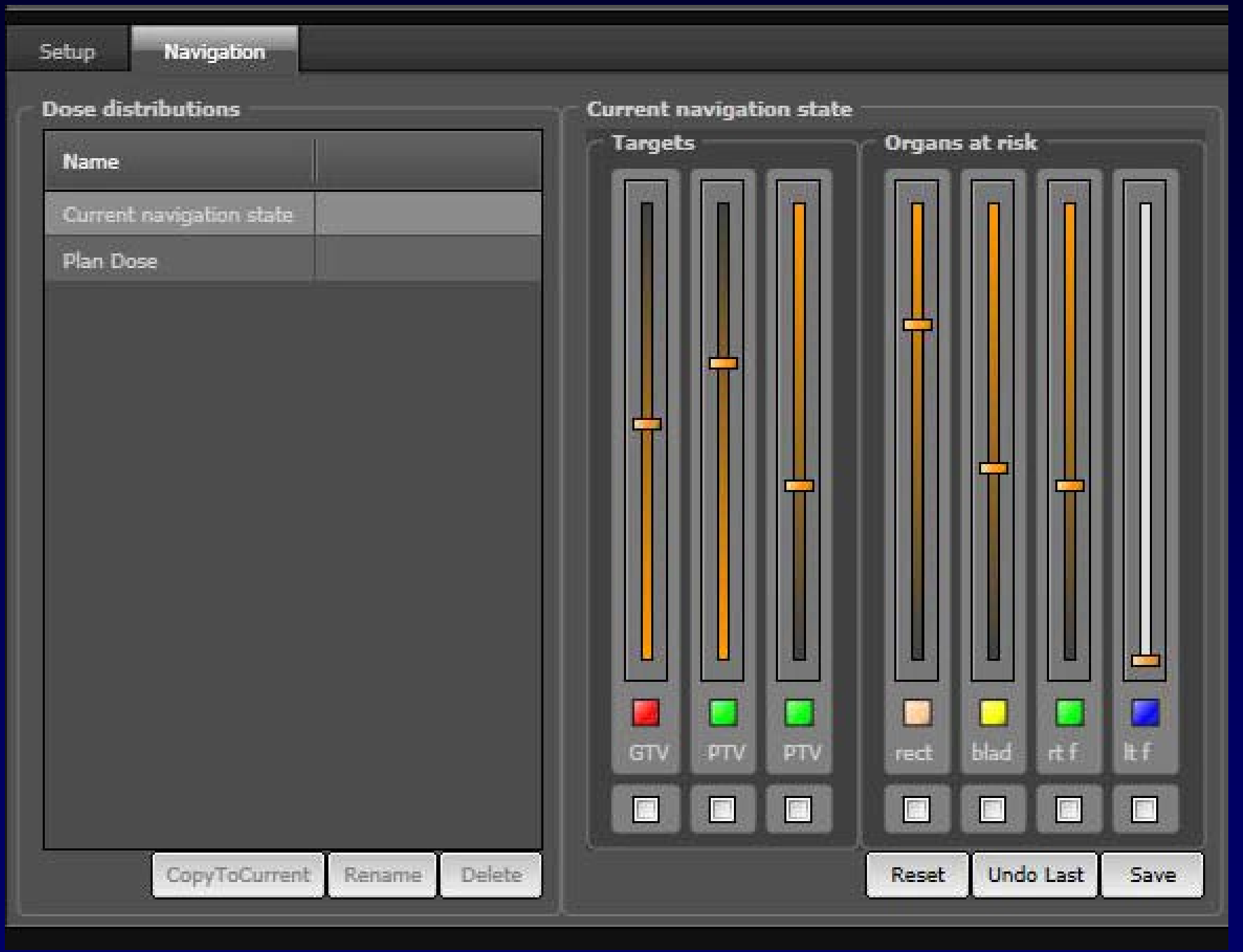
ROI	Description
GTV	Min Dose 4,500.00 cGy
PTV_45	Min Dose 4,500.00 cGy
PTV_45	Max Dose 4,600.00 cGy
rectum	Max EUD 2,000.00 cGy, Parameter
bladder	Max EUD 2,700.00 cGy, Parameter
rt femoral hea	Max EUD 1,000.00 cGy, Parameter
lt femoral hea	Max EUD 1,000.00 cGy, Parameter

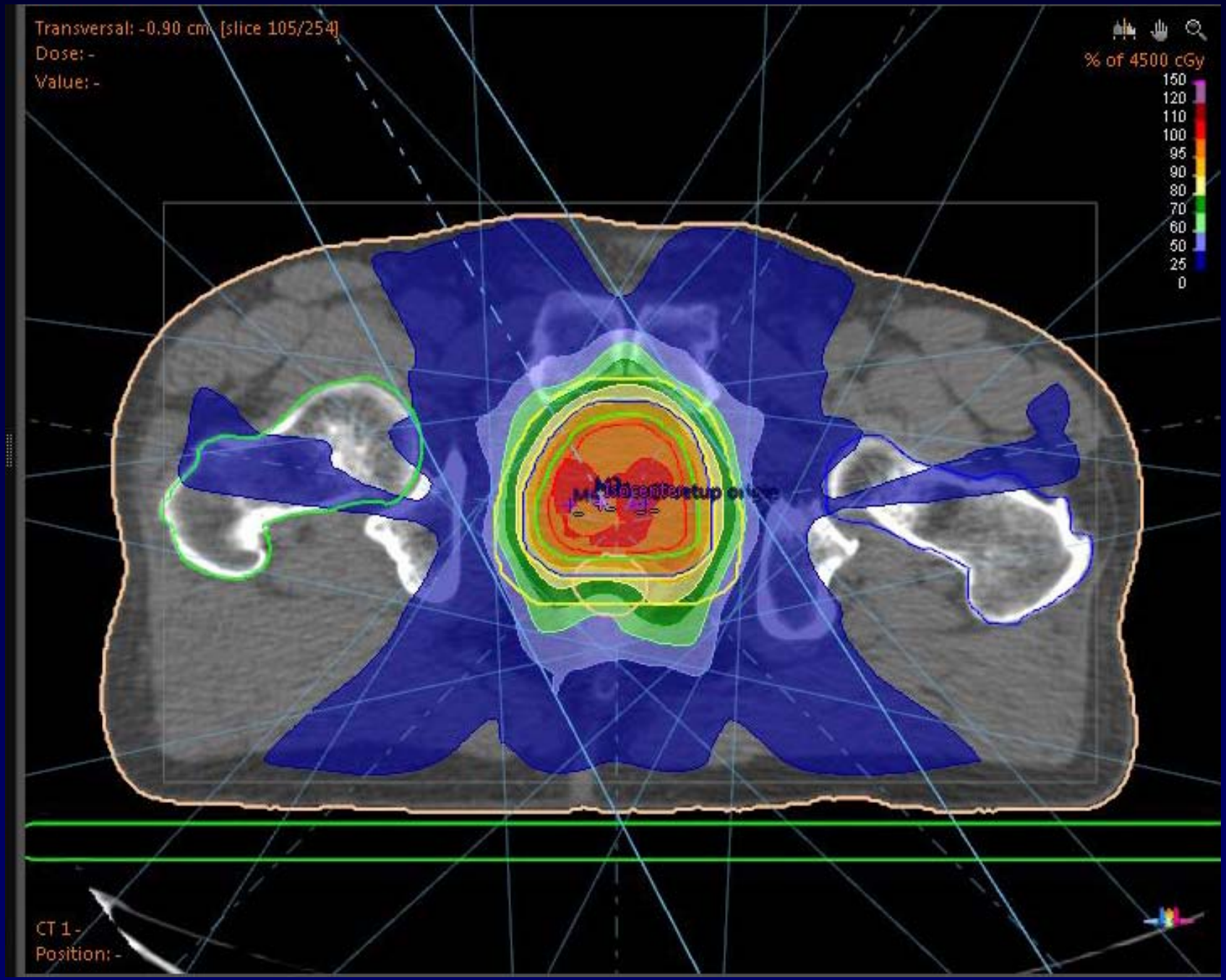
Add... | Edit... | Delete

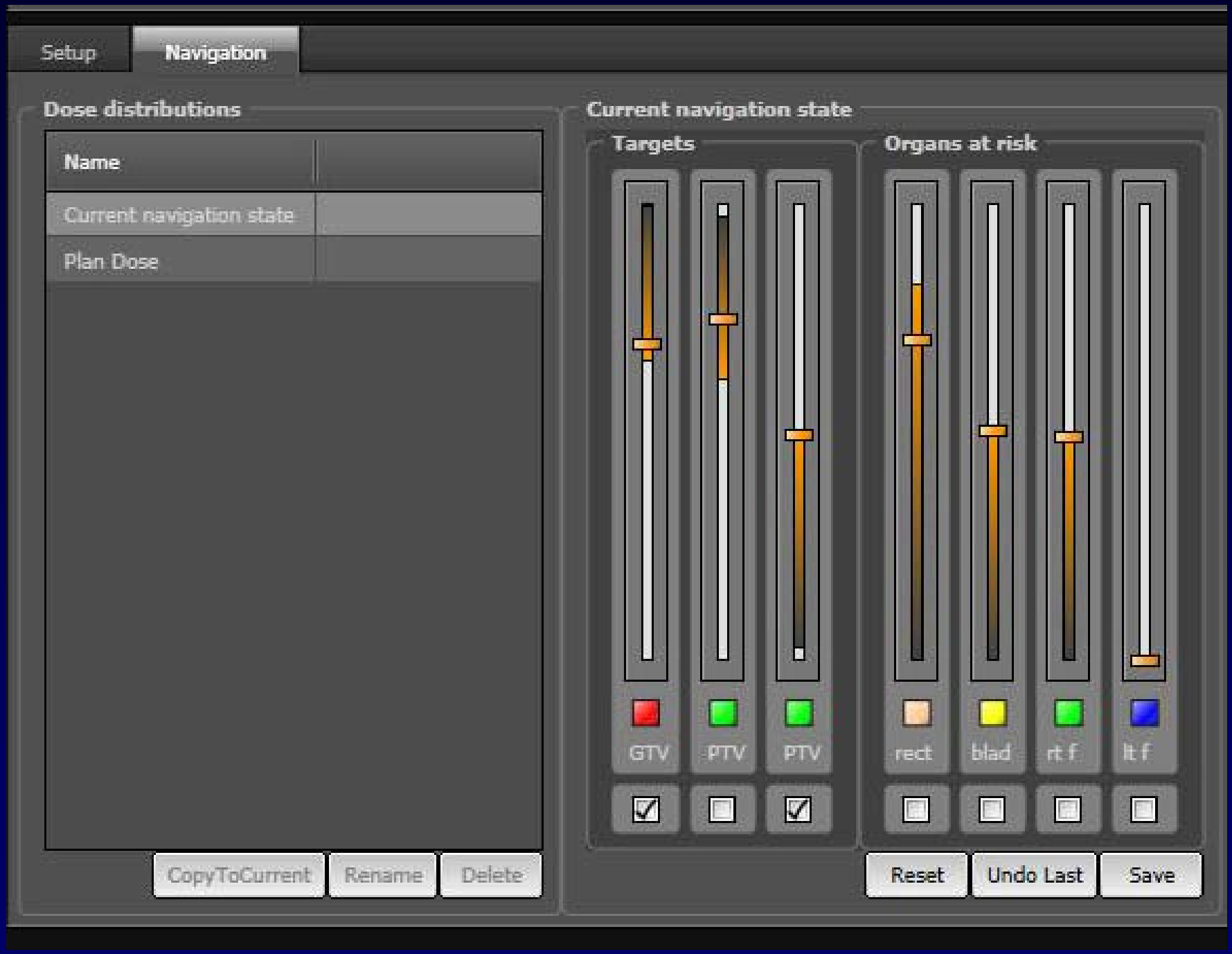
Constraints

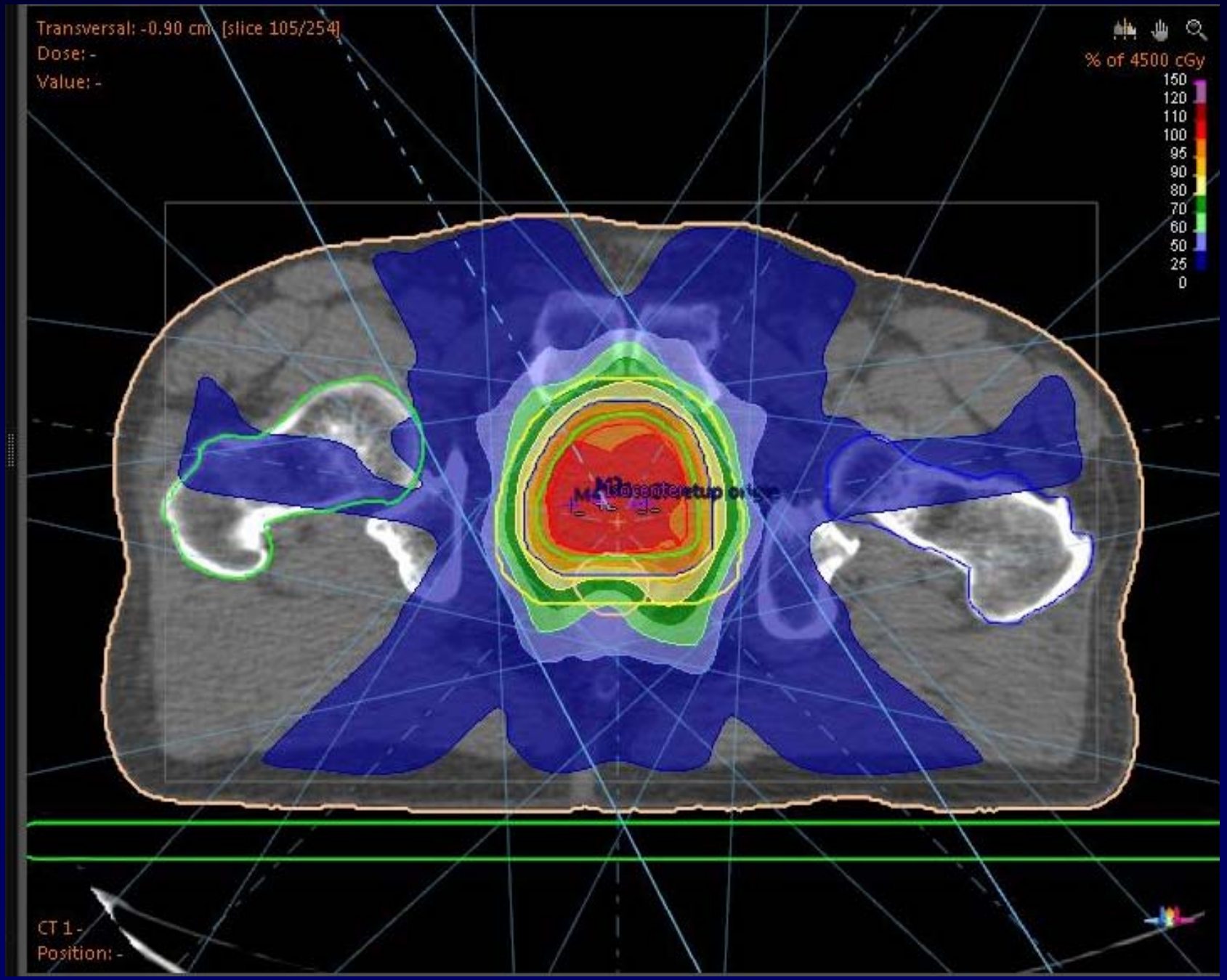
ROI	Description
rectum	Max DVH 3,000.00 cGy, to 45% Volume
bladder	Max DVH 4,000.00 cGy, to 50% Volume
GTV	Min DVH 4,275.00 cGy, to 90% Volume
PTV_45	Min DVH 4,275.00 cGy, to 80% Volume
PTV_45	Max Dose 5,000.00 cGy

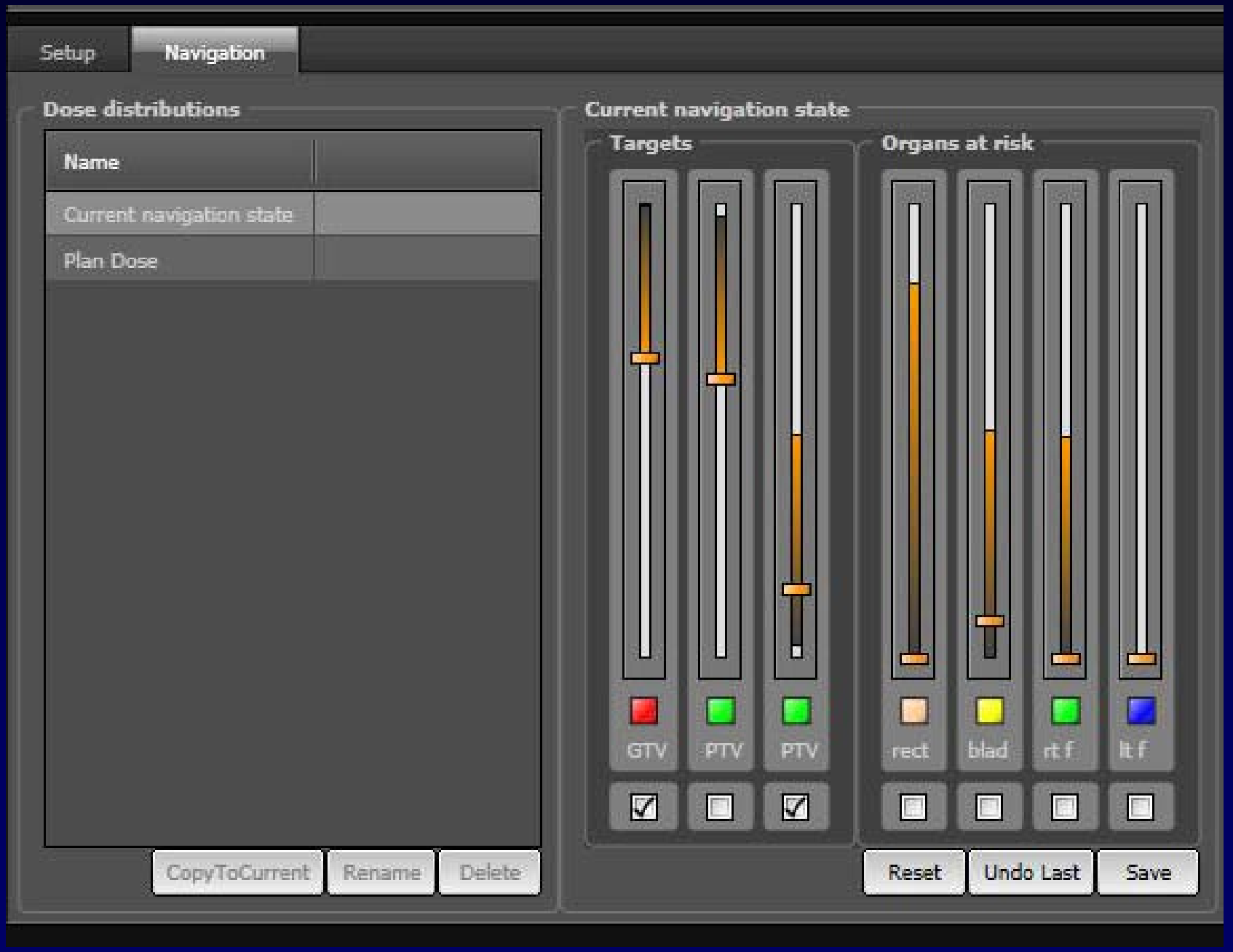
Add... | Edit... | Delete

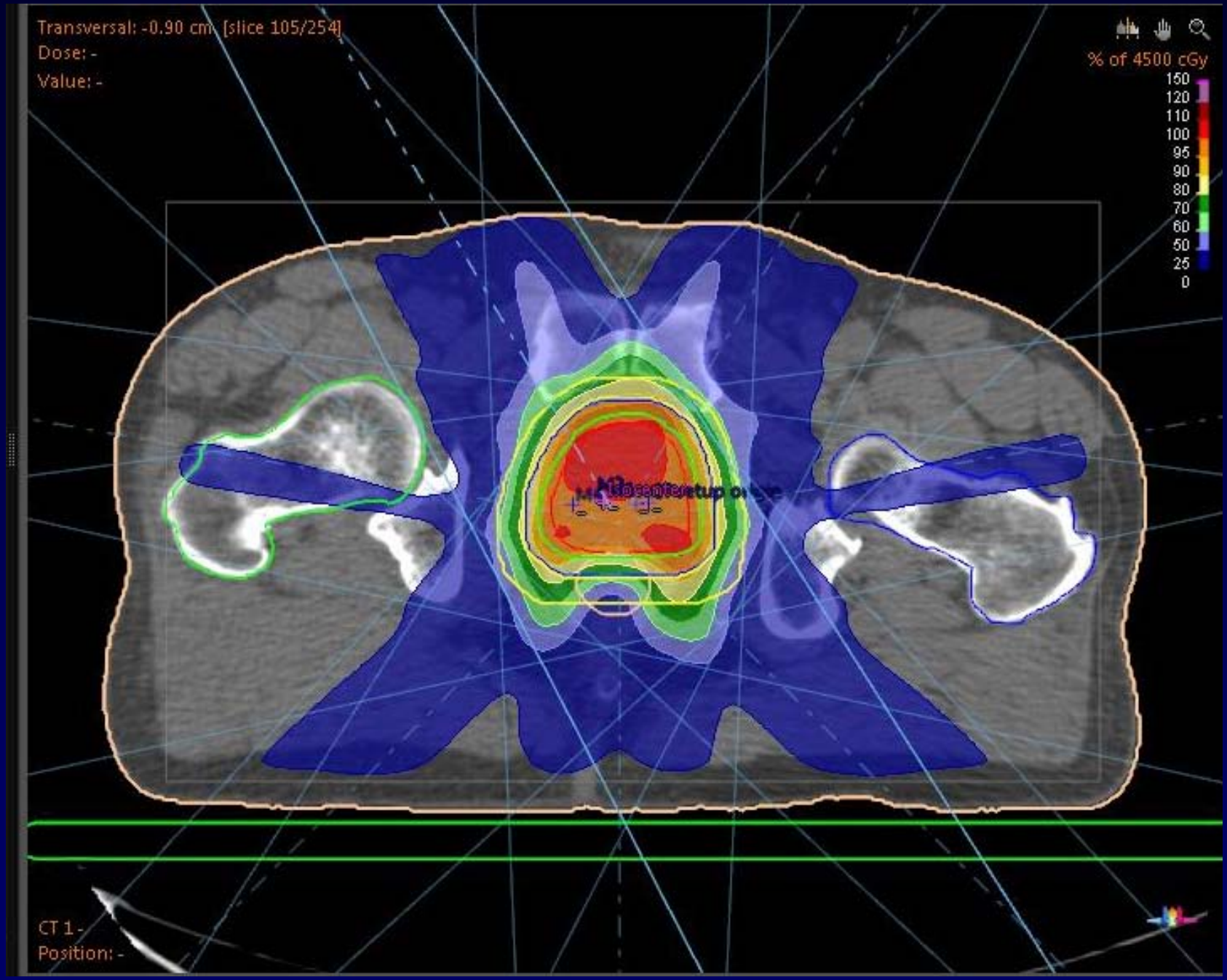

Setup
Navigation
Dose distributions
Name
Current navigation state
Plan Dose
CopyToCurrent
Rename
Delete
Current navigation state
Targets
Organs at risk
GTV
PTV
PTV
rect
blad
rt f
lt f
Reset
Undo Last
Save


Transversal: -0.90 cm [slice 105/254]
Dose: -
Value: -
% of 4500 cGy
150
120
110
100
95
90
80
70
60
50
25
0
CT 1 -
Position: -


Setup
Navigation
Dose distributions
Name
Current navigation state
Plan Dose
CopyToCurrent
Rename
Delete
Current navigation state
Targets
Organs at risk
GTV
PTV
PTV
rect
blad
rt f
lt f
Reset
Undo Last
Save


Transversal: -0.90 cm [slice 105/254]
Dose: -
Value: -
% of 4500 cGy
150
120
110
100
95
90
80
70
60
50
25
0
CT 1 -
Position: -


Setup
Navigation
Dose distributions
Name
Current navigation state
Plan Dose
CopyToCurrent
Rename
Delete
Current navigation state
Targets
Organs at risk
GTV
PTV
PTV
rect
blad
rt f
lt f
Reset
Undo Last
Save


Transversal: -0.90 cm [slice 105/254]
Dose: -
Value: -
% of 4500 cGy
150
120
110
100
95
90
80
70
60
50
25
0
CT 1 -
Position: -

- Symposium on MCO on Tuesday at 4 pm (Room 204C).

Plan Optimization - Summary

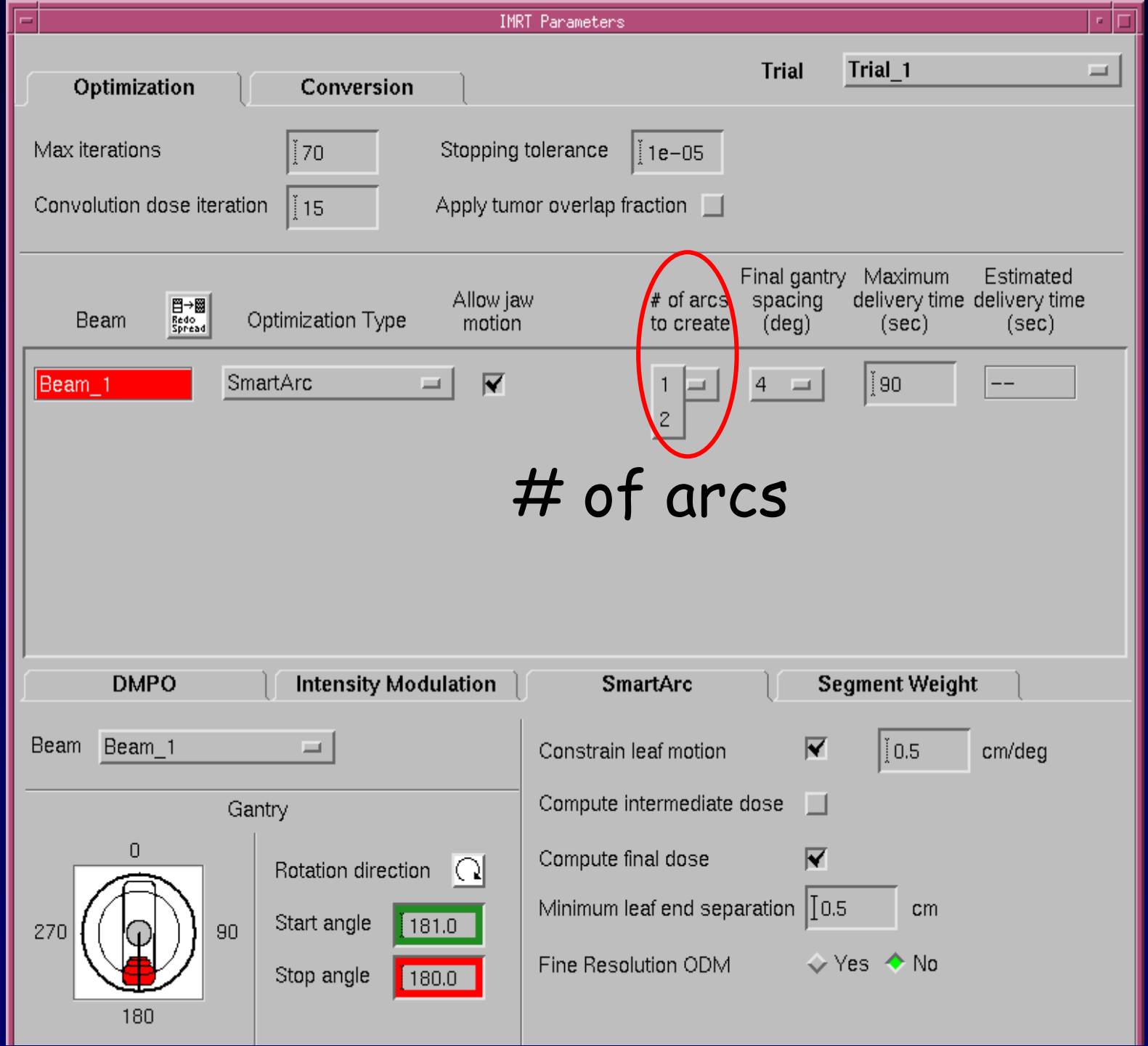
- Developing a base understanding of optimization terminology and techniques assists in maximizing the capabilities of inverse planning solutions.
- There is a wide variation in the quality of inverse planning solutions on the market.
- The future may provide us with more interactive tools that should speed up the planning process and provide improved plan quality.

Thank you!!

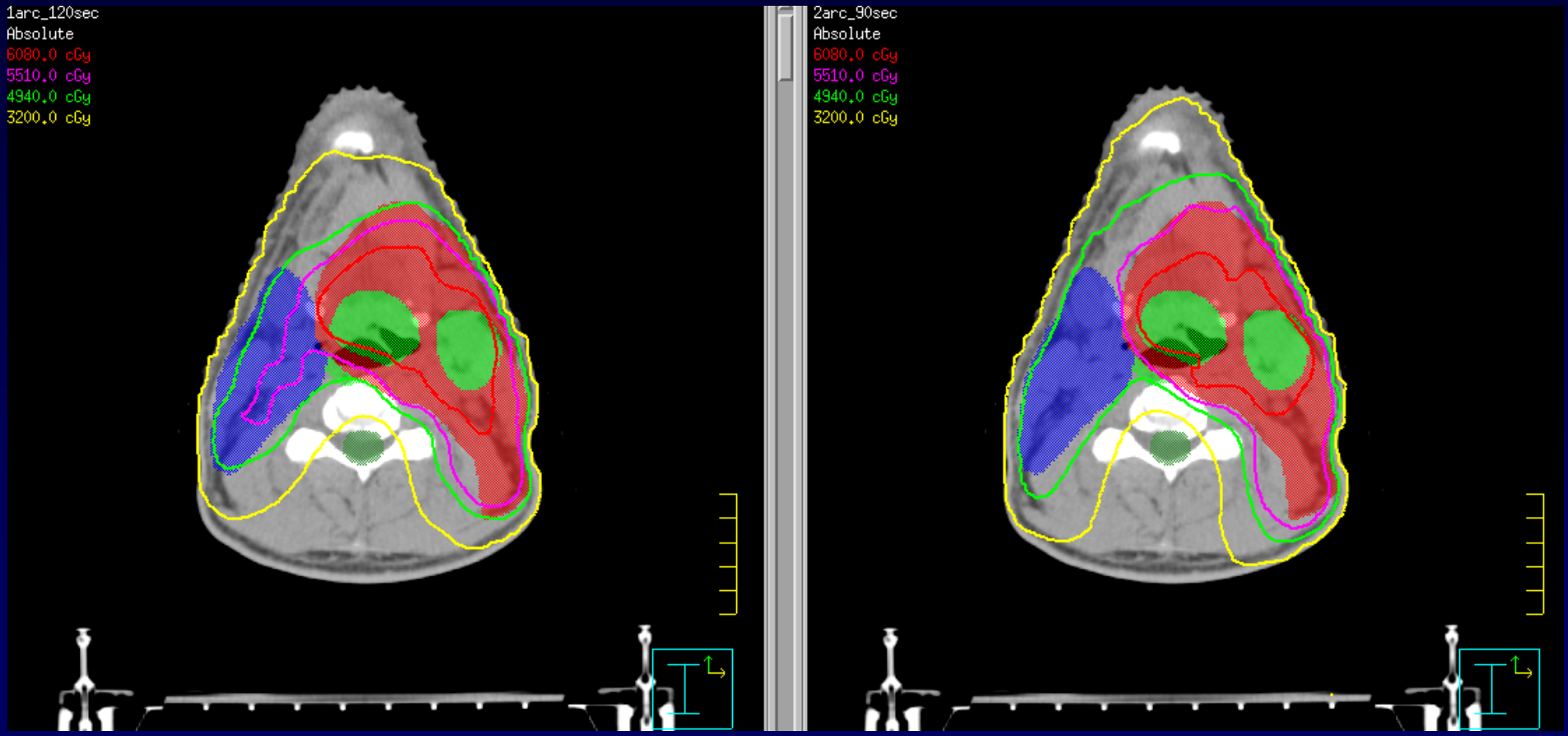
of arcs

- The user can set up one arc and have SmartArc create a dual arc plan where the second arc has the same setup as the first, but rotates in the opposite direction.
- The algorithm behind the dual arc feature strives to reduce leaf travel by distributing control points between the two arcs based on the shapes of the segments.

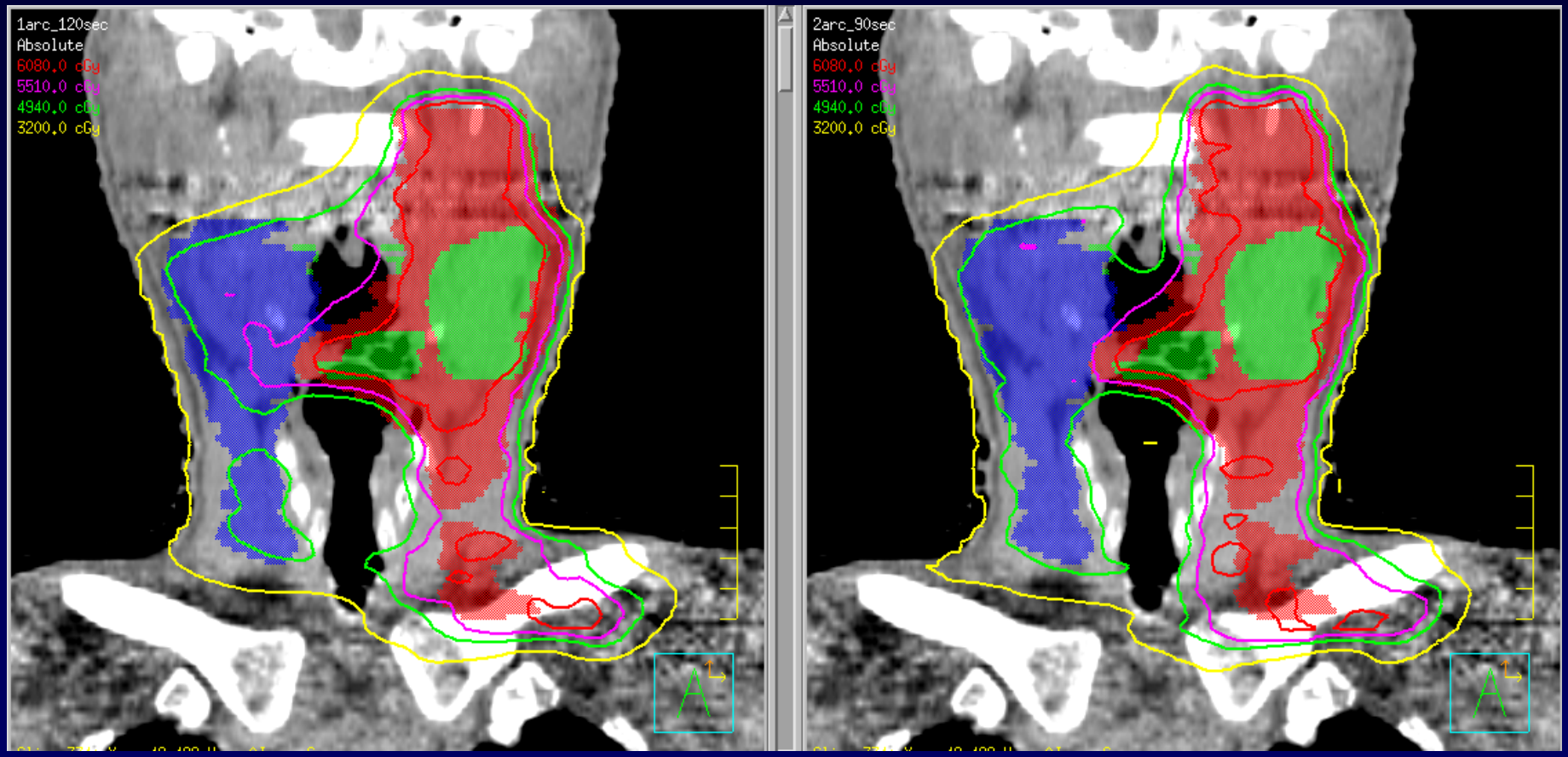
Courtesy of Karl Bzdusek


IMRT Parameters
Trial
Trial_1
Optimization
Conversion
Max iterations
70
Stopping tolerance
1e-05
Convolution dose iteration
15
Apply tumor overlap fraction
Beam
Redo Spread
Optimization Type
Allow jaw motion
# of arcs to create
Final gantry spacing (deg)
Maximum delivery time (sec)
Estimated delivery time (sec)
Beam_1
SmartArc
1
2
4
90
--
# of arcs
DMPO
Intensity Modulation
SmartArc
Segment Weight
Beam
Beam_1
Gantry
0
270
90
180
Rotation direction
Start angle
181.0
Stop angle
180.0
Constrain leaf motion
0.5
cm/deg
Compute intermediate dose
Compute final dose
Minimum leaf end separation
0.5
cm
Fine Resolution ODM
Yes
No

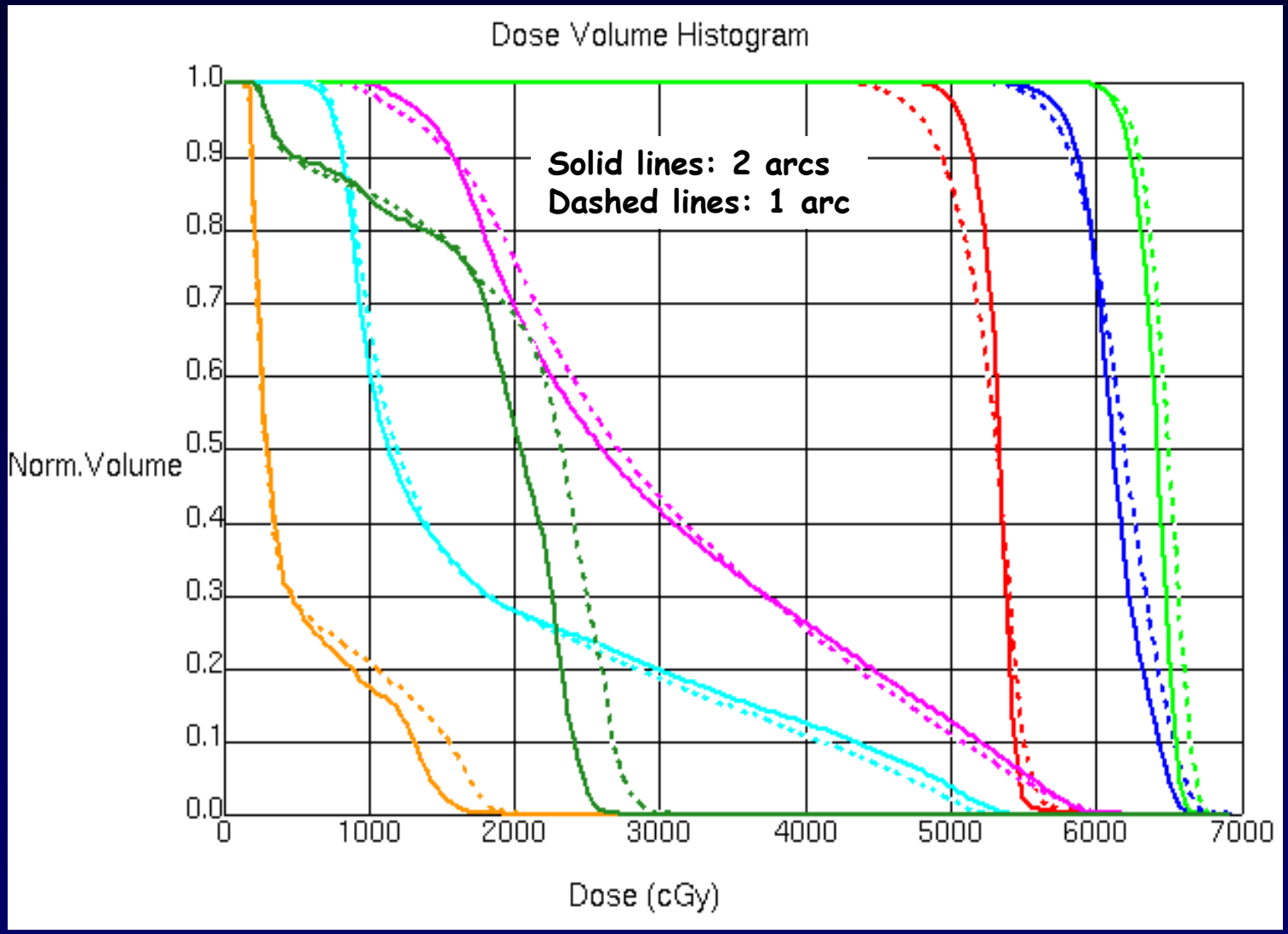
1 arc vs. 2 arcs



1 arc vs. 2 arcs

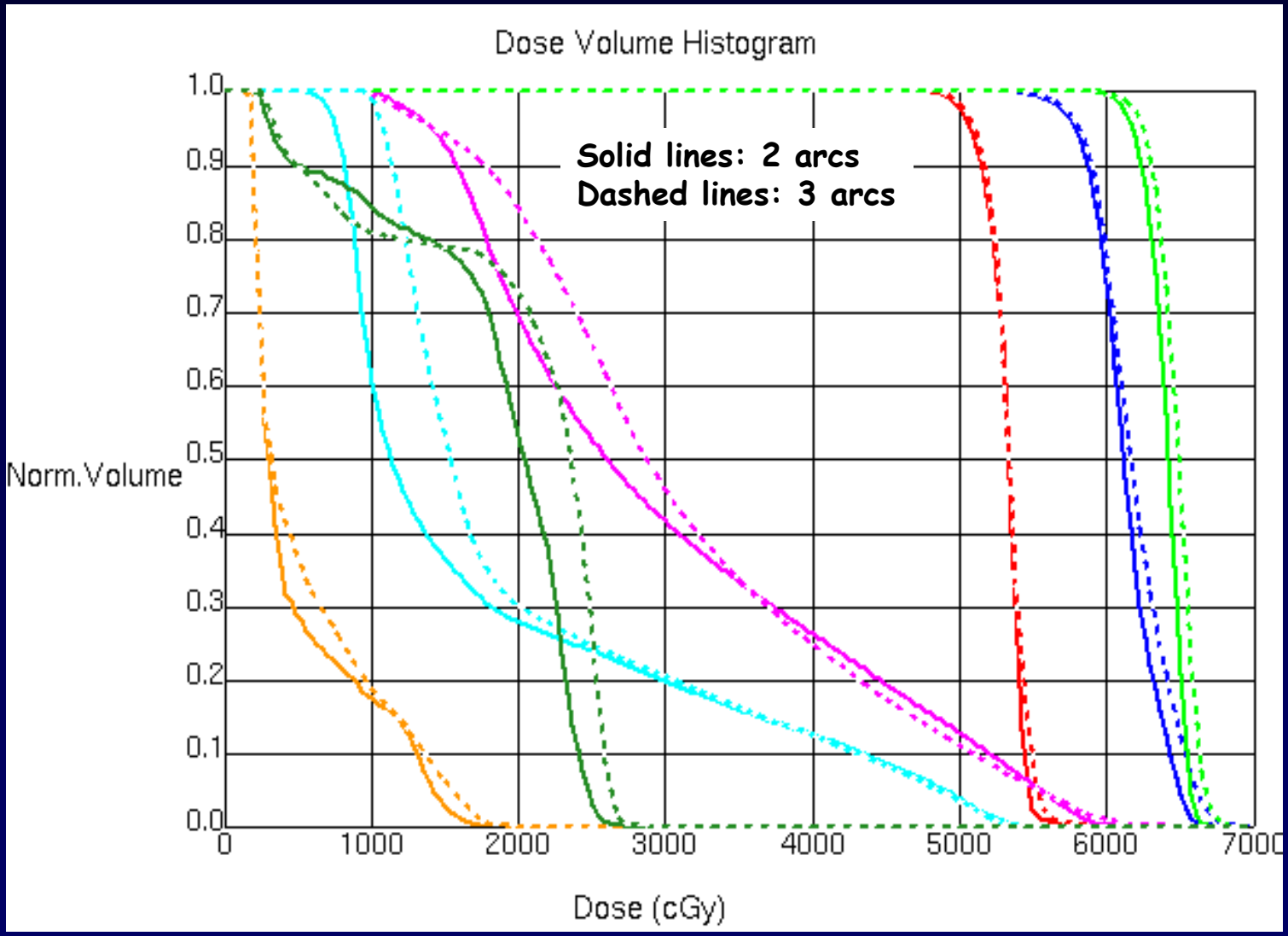


1 arc vs. 2 arcs

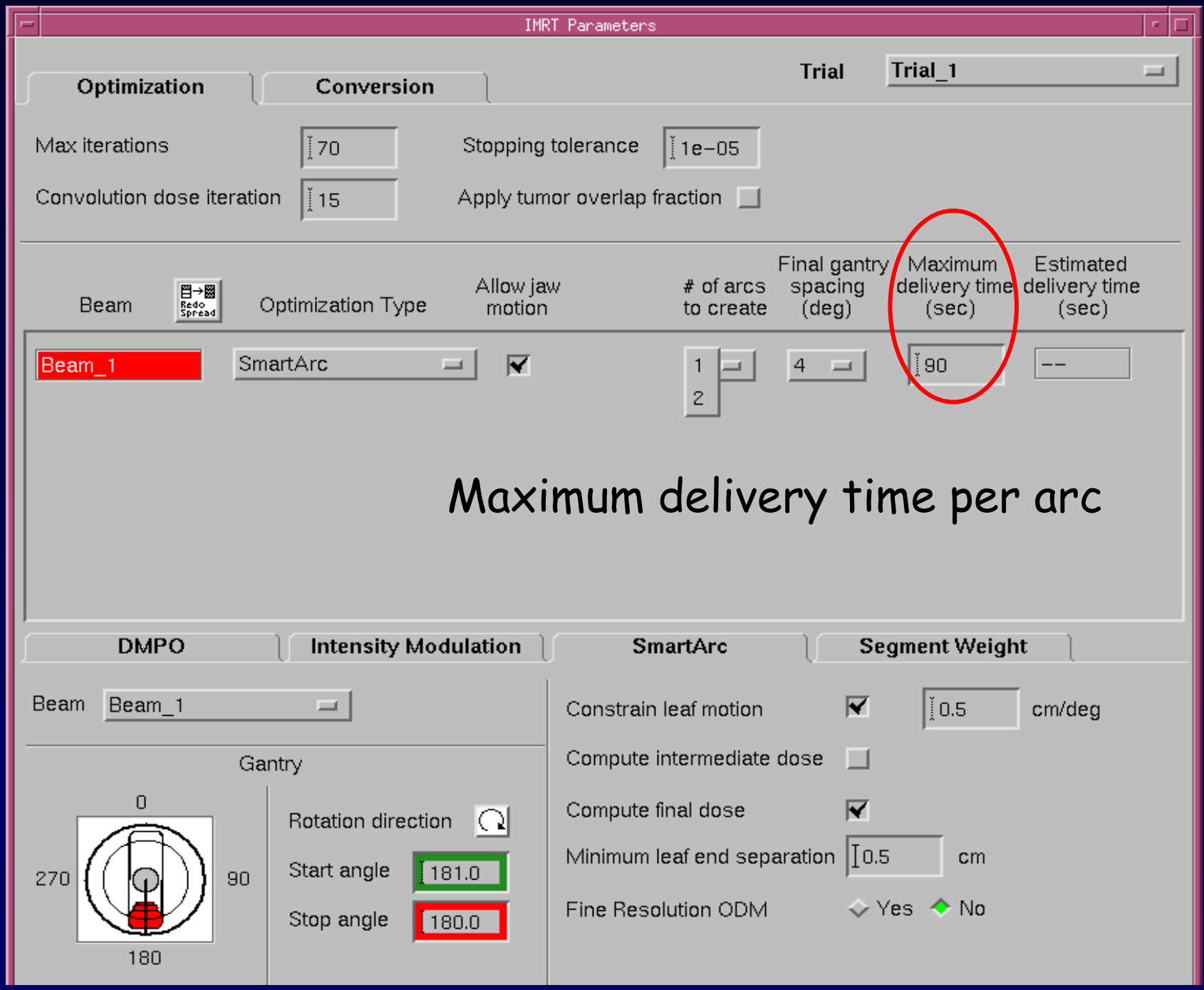


Delivery time: 1 arc= 124 sec, 2 arcs = 181 sec

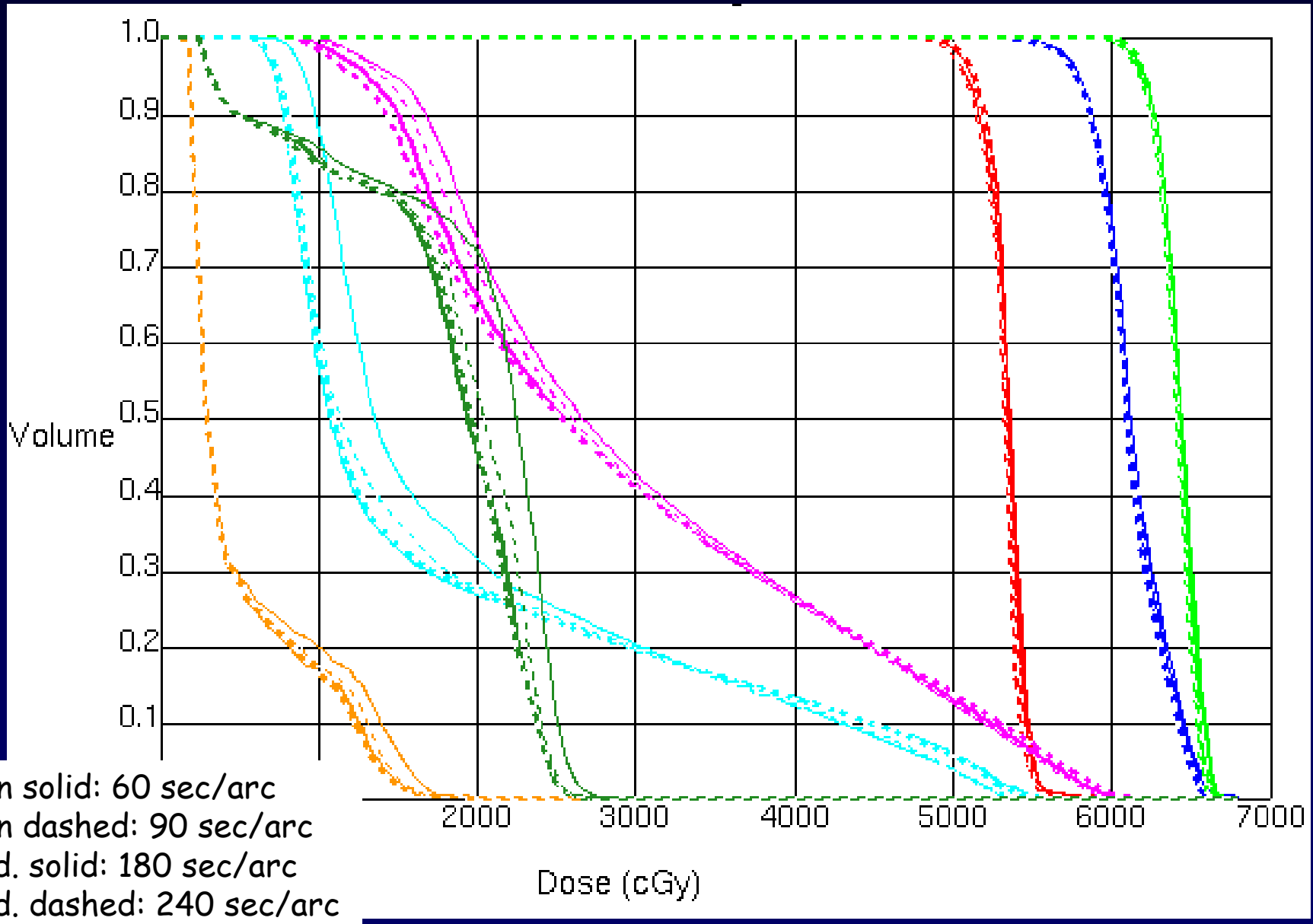
2 arcs vs. 3 arcs



Delivery time: 2 arcs = 181 sec, 3 arcs: 293 sec


IMRT Parameters
Optimization
Conversion
Trial
Trial_1
Max iterations
70
Stopping tolerance
1e-05
Convolution dose iteration
15
Apply tumor overlap fraction
Beam
Redo Spread
Optimization Type
Allow jaw motion
# of arcs to create
Final gantry spacing (deg)
Maximum delivery time (sec)
Estimated delivery time (sec)
Beam_1
SmartArc
1
2
4
90
--
Maximum delivery time per arc
DMPO
Intensity Modulation
SmartArc
Segment Weight
Beam
Beam_1
Gantry
0
270
90
180
Rotation direction
Start angle
181.0
Stop angle
180.0
Constrain leaf motion
0.5
cm/deg
Compute intermediate dose
Compute final dose
Minimum leaf end separation
0.5
cm
Fine Resolution ODM
Yes
No

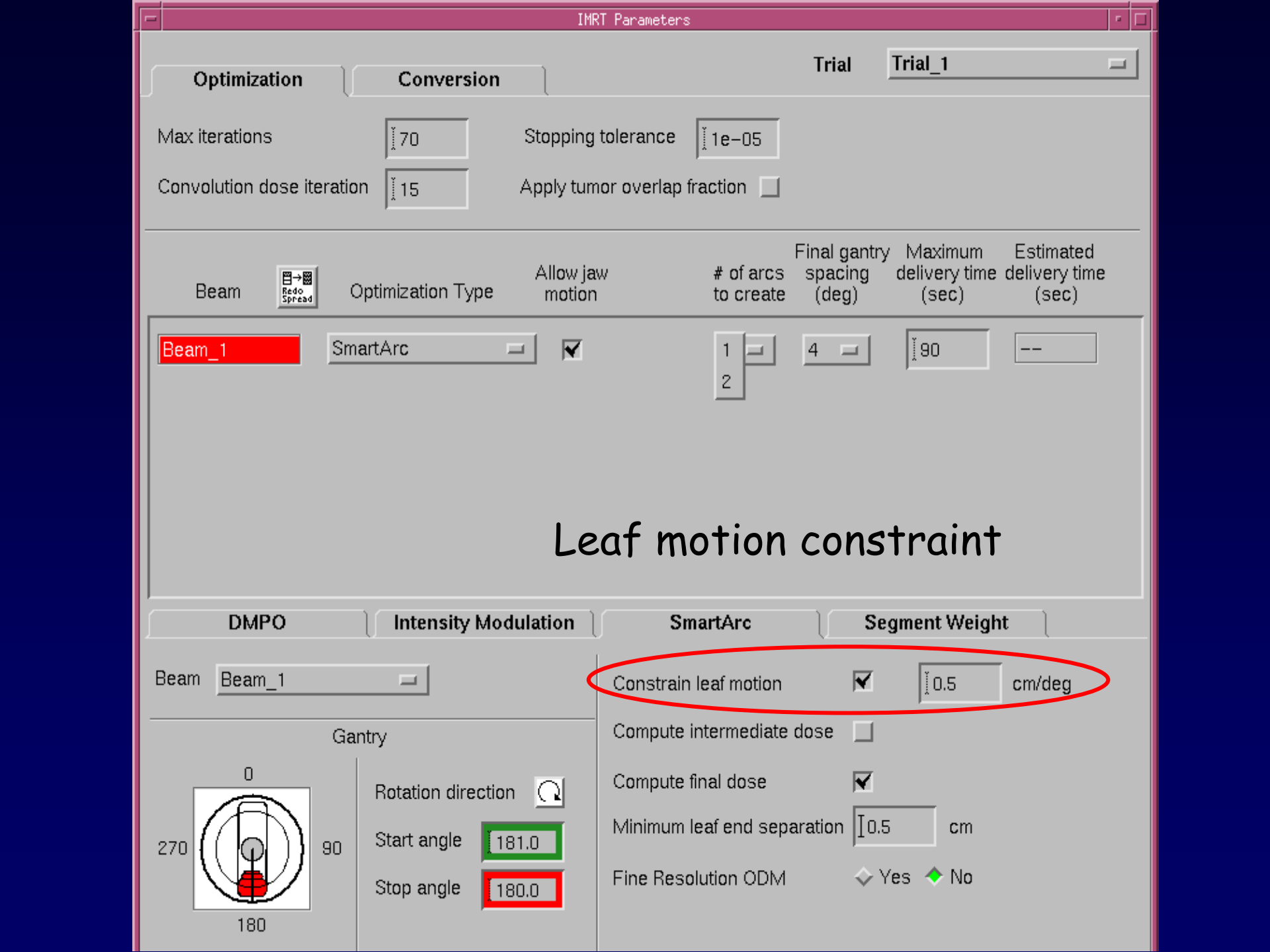
Delivery time



Thin solid: 60 sec/arc
Thin dashed: 90 sec/arc
Med. solid: 180 sec/arc
Med. dashed: 240 sec/arc

Delivery time

Maximum time (sec/arc)	Estimated time (sec)
60	140
90	181
180	325
240	356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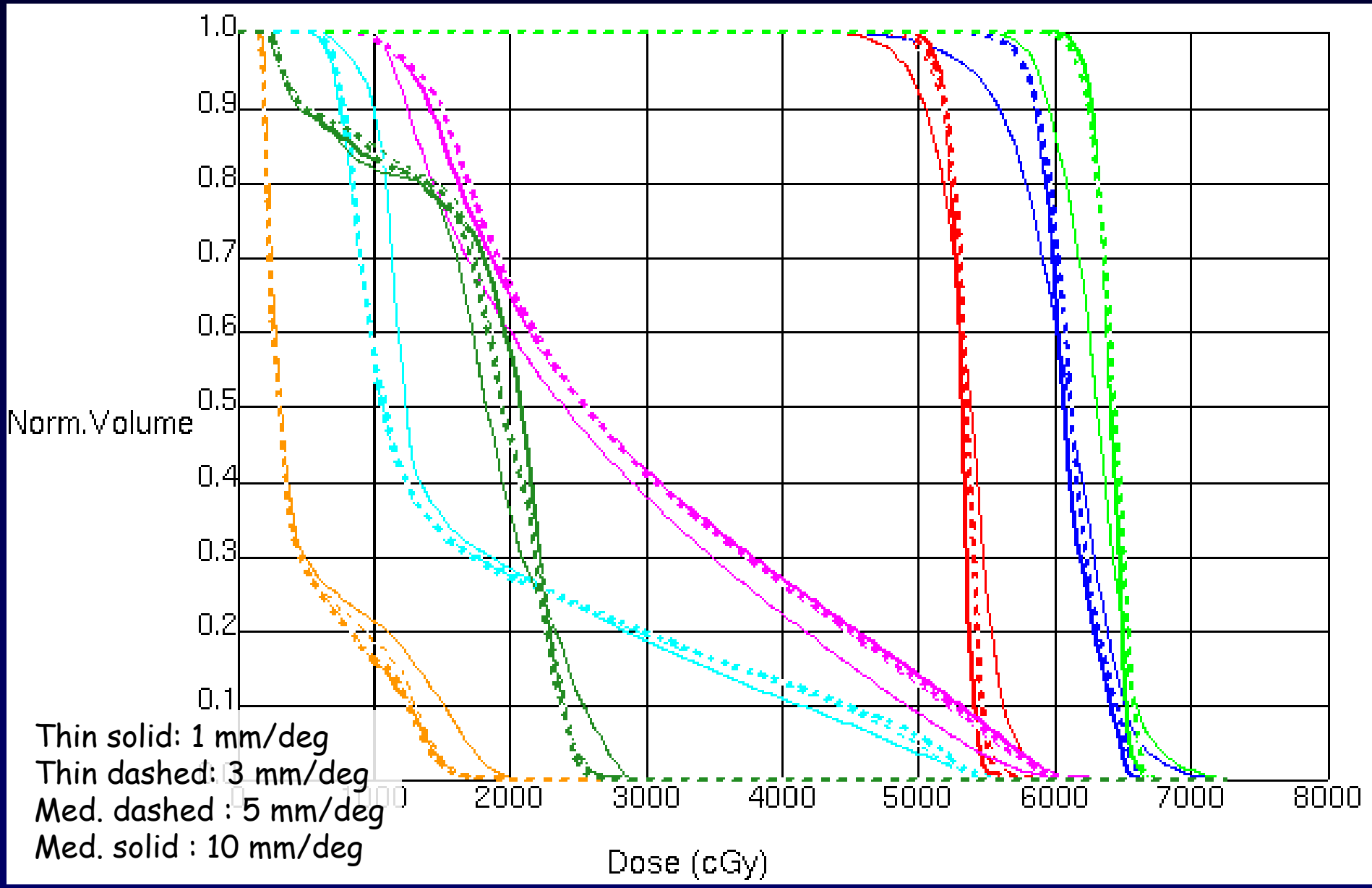
Optimization
Conversion
Trial
Trial_1
Max iterations
70
Stopping tolerance
1e-05
Convolution dose iteration
15
Apply tumor overlap fraction
Beam
Redo Spread
Optimization Type
Allow jaw motion
# of arcs to create
Final gantry spacing (deg)
Maximum delivery time (sec)
Estimated delivery time (sec)
Beam_1
SmartArc
1
2
4
90
--
Leaf motion constraint
DMPO
Intensity Modulation
SmartArc
Segment Weight
Beam
Beam_1
Constrain leaf motion
0.5
cm/deg
Compute intermediate dose
Compute final dose
Minimum leaf end separation
0.5
cm
Fine Resolution ODM
Yes
No
Gantry
0
270
90
180
Rotation direction
Start angle
181.0
Stop angle
180.0

Leaf motion


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Norm.Volume
2000
3000
4000
5000
6000
7000
8000
Dose (cGy)
Thin solid: 1 mm/deg
Thin dashed: 3 mm/deg
Med. dashed : 5 mm/deg
Med. solid : 10 mm/deg

Leaf motion

Leaf motion (mm/deg)	1	3	5	10
Estimated delivery time (sec)	303	315	325	376
Actual delivery time (sec)	218	250	300	427
QA passing rate (%)	98.3	99.0	98.7	98.1

SmartArc Planning Parameters

- 1 arc is sufficient for simple cases such as prostate, but 2 arcs are needed for more complex cases such as H&N.
- We typically set a delivery time of 90sec/arc.
- We generally restrict the leaf motion to be 3mm/degree of gantry rotation for prostate cases and 4 or 5mm/degree for H&N cases.

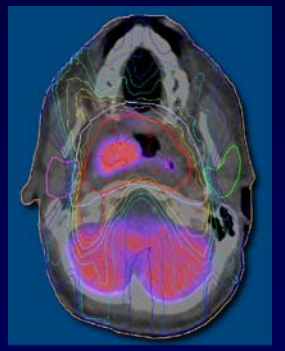
SWEDISH

Biological Modeling

Biological cost functions allow us to model tissue-specific dose responses, that is the *volume effect*.

Serial
(small volume effect)

Parallel
(large volume effect)

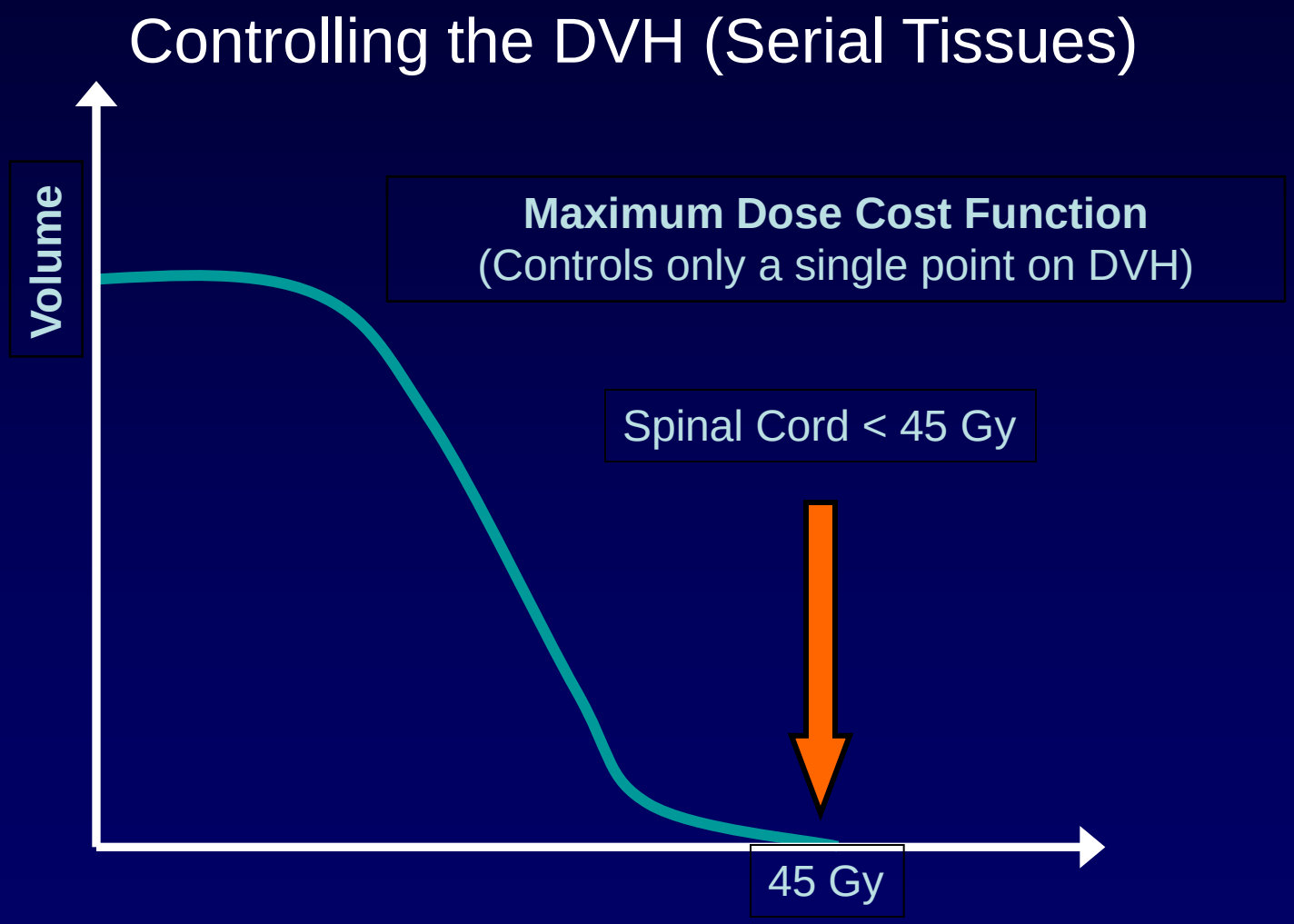


Tumor
(sensitive to cold spots)

But, for treatment planning, these cost functions really allow us to *control the shape of the DVH…*

Courtesy of Elekta

Biological Modeling: Controlling the DVH
Serial Tissues

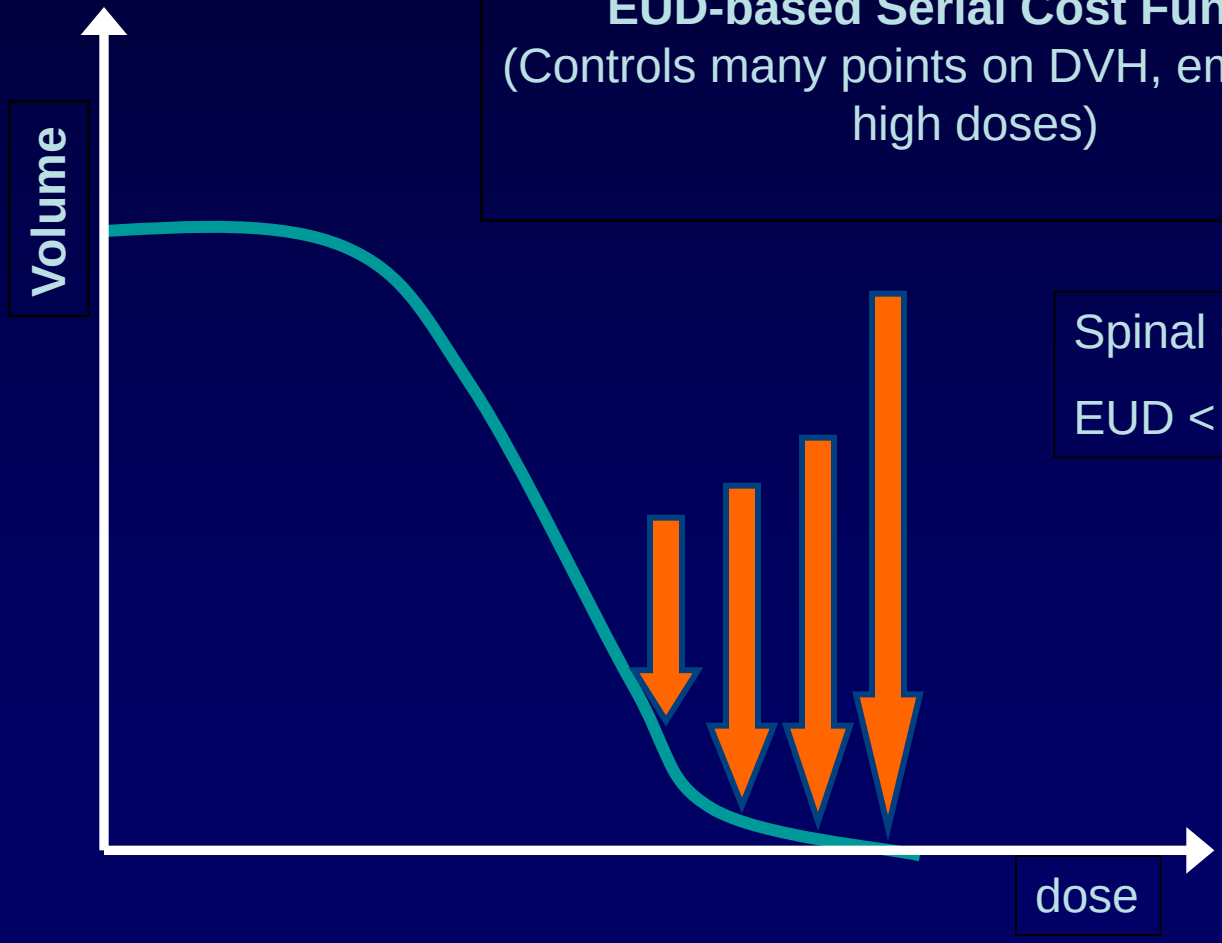


Courtesy of Elekta

Biological Modeling: Controlling the DVH Serial Tissues

Controlling the DVH (Serial Tissues)

EUD-based Serial Cost Function
(Controls many points on DVH, emphasis on high doses)

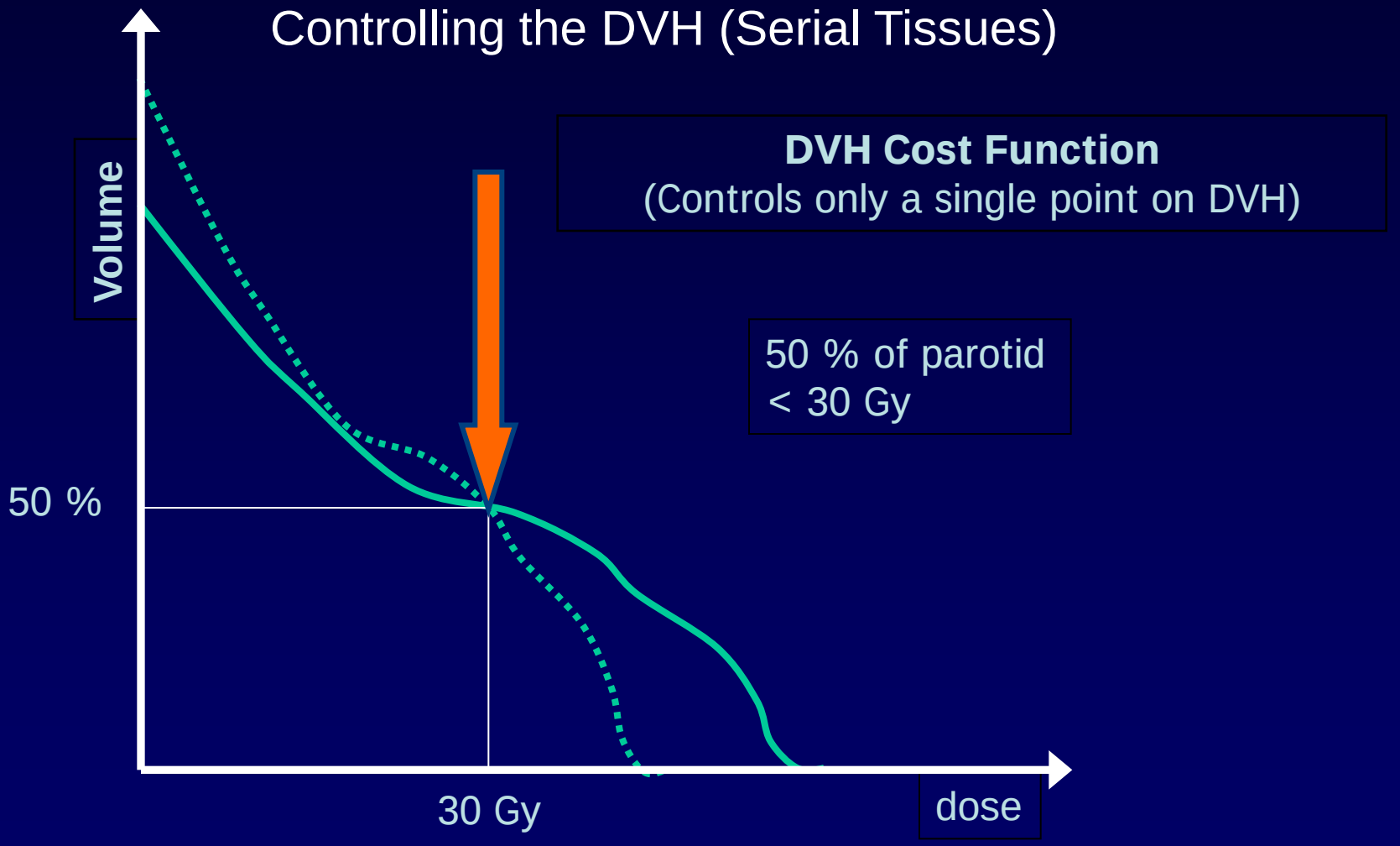


Spinal Cord

EUD < 35 Gy

Courtesy of Elekta

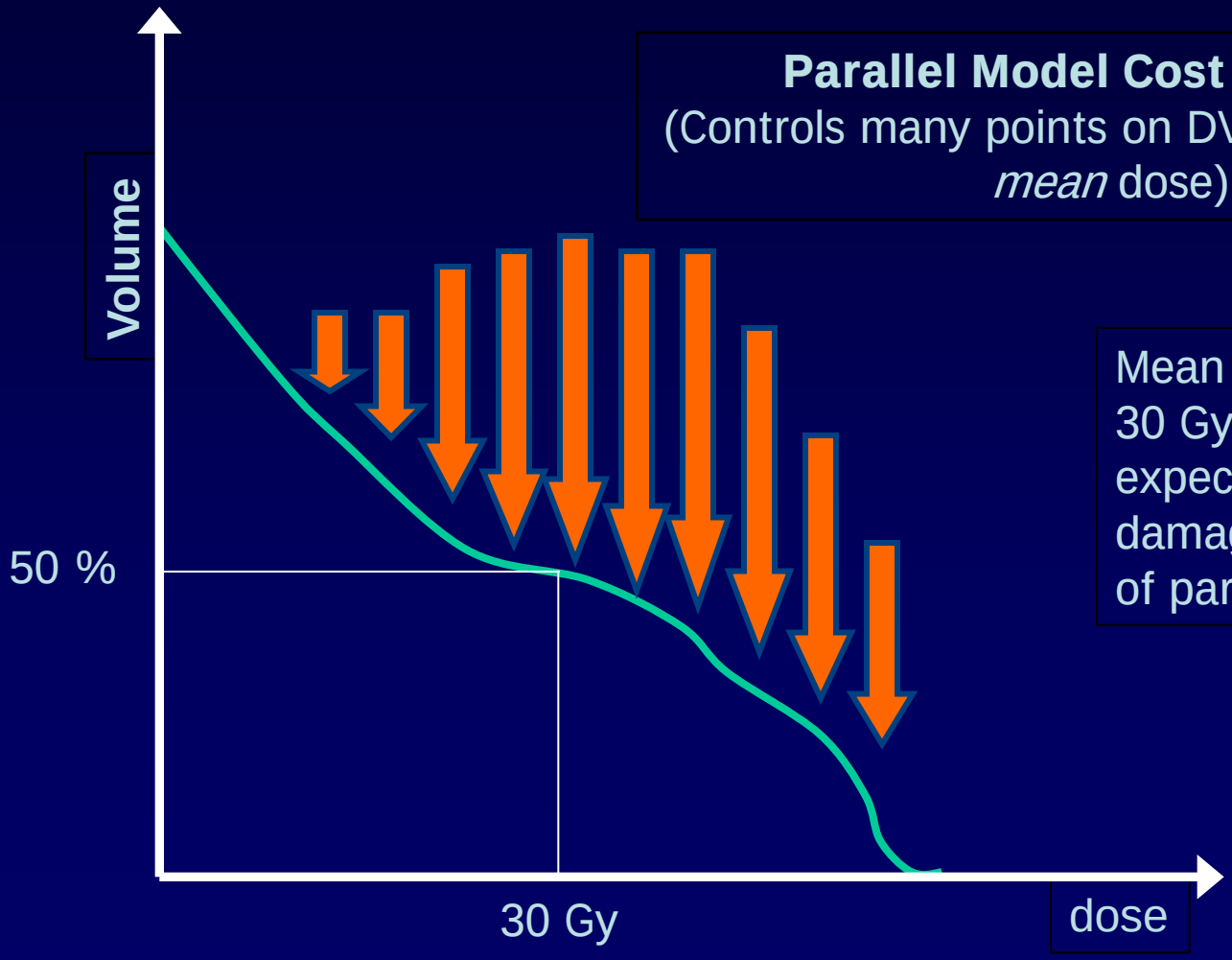
Biological Modeling: Controlling the DVH Parallel Tissues



Courtesy of Elekta

Biological Modeling: Controlling the DVH Parallel Tissues

Controlling the DVH (Serial Tissues)



Parallel Model Cost Function
(Controls many points on DVH, emphasis on *mean* dose)

Mean dose of 30 Gy is expected to damage 50 % of parotid

Courtesy of Elekta

Optimization via Simulated Annealing

1) A pencil beam is selected randomly.
2) The pencil beam weight is changed by a random amount.
3) The new dose distribution is determined along with the corresponding objective function.
4) Objective function lower: accept change.
5) Objective function higher: accept change with certain probability.

Direct aperture optimization: A turnkey solution for step-and-shoot IMRT

D. M. Shepard, M. A. Earl, X. A. Li, S. Naqvi, and C. Yu
University of Maryland School of Medicine, Department of Radiation Oncology, 22 South Greene St., Baltimore, Maryland 21201-1595

(Received 26 September 2001; accepted for publication 12 March 2002; published 13 May 2002)

IMRT treatment plans for step-and-shoot delivery have traditionally been produced through the optimization of intensity distributions (or maps) for each beam angle. The optimization step is followed by the application of a leaf-sequencing algorithm that translates each intensity map into a set of deliverable aperture shapes. In this article, we introduce an automated planning system in which we bypass the traditional intensity optimization, and instead directly optimize the shapes and the weights of the apertures. We call this approach "direct aperture optimization." This technique allows the user to specify the maximum number of apertures per beam direction, and hence provides significant control over the complexity of the treatment delivery. This is possible because the machine dependent delivery constraints imposed by the MLC are enforced within the aperture optimization algorithm rather than in a separate leaf-sequencing step. The leaf settings and the aperture intensities are optimized simultaneously using a simulated annealing algorithm. We have tested direct aperture optimization on a variety of patient cases using the EGS4/BEAM Monte Carlo package for our dose calculation engine. The results demonstrate that direct aperture optimization can produce highly conformal step-and-shoot treatment plans using only three to five apertures per beam direction. As compared with traditional optimization strategies, our studies demonstrate that direct aperture optimization can result in a significant reduction in both the number of beam segments and the number of monitor units. Direct aperture optimization therefore produces highly efficient treatment deliveries that maintain the full dosimetric benefits of IMRT. [DOI: 10.1118/1.1477415]

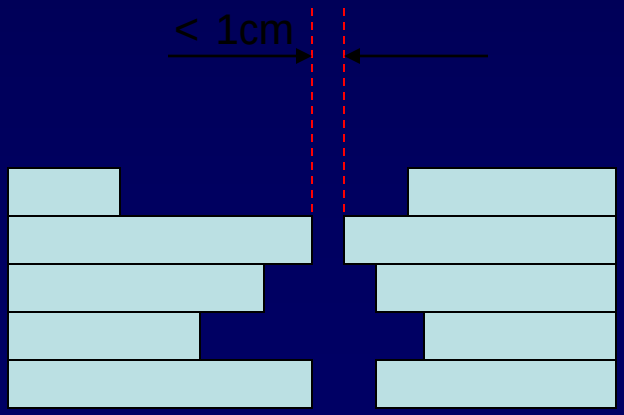
Key words: IMRT, inverse treatment planning, optimization, intensity modulation

MLC Constraints

Every multi-leaf collimator has delivery constraints:

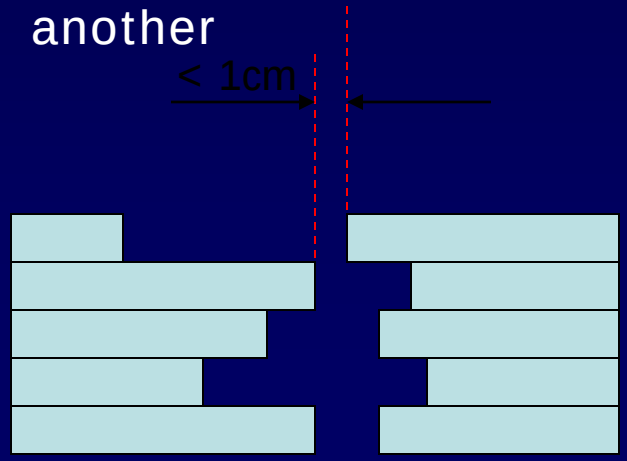
Some sample Elekta constraints:

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

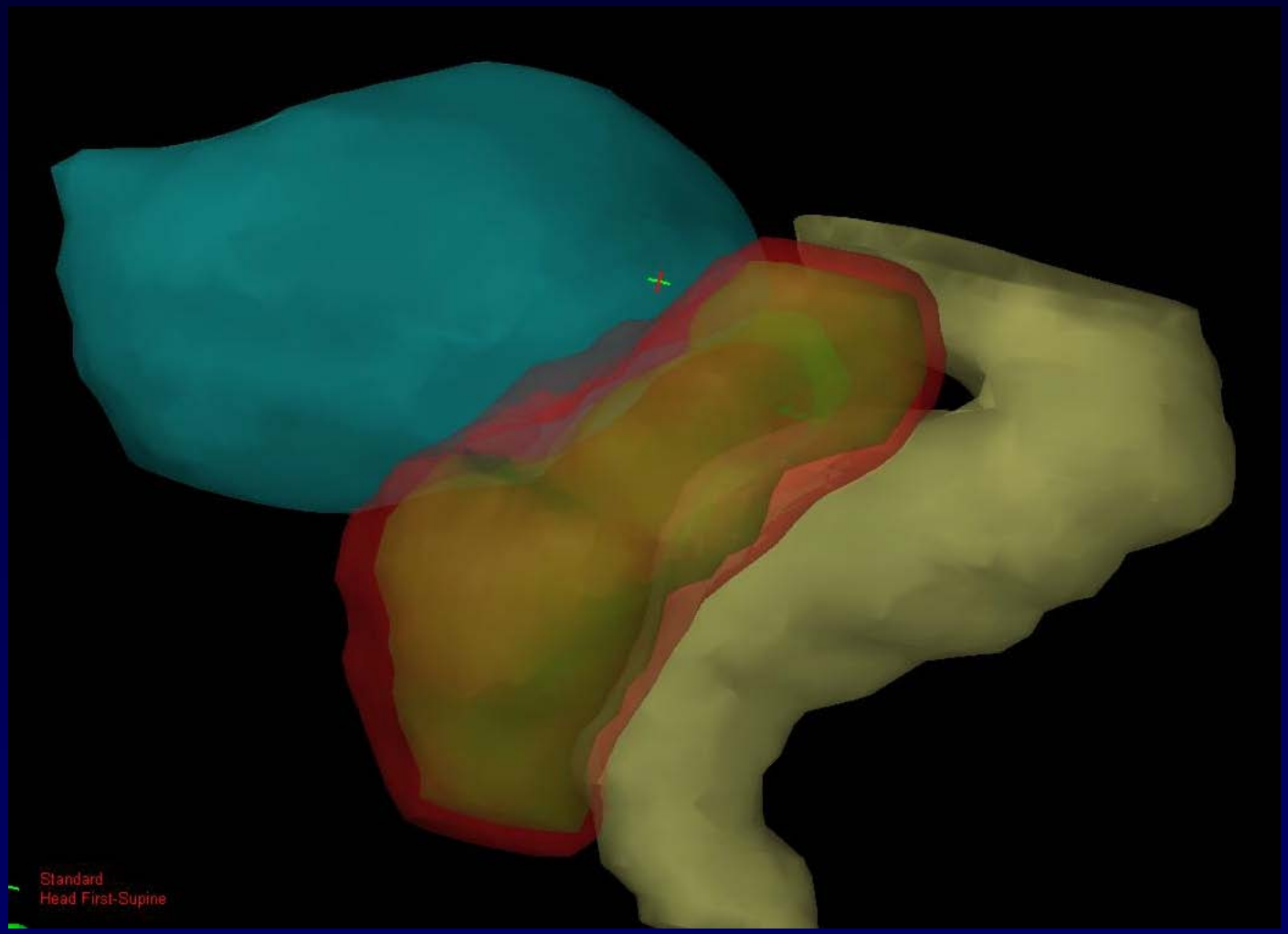


Not allowed

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

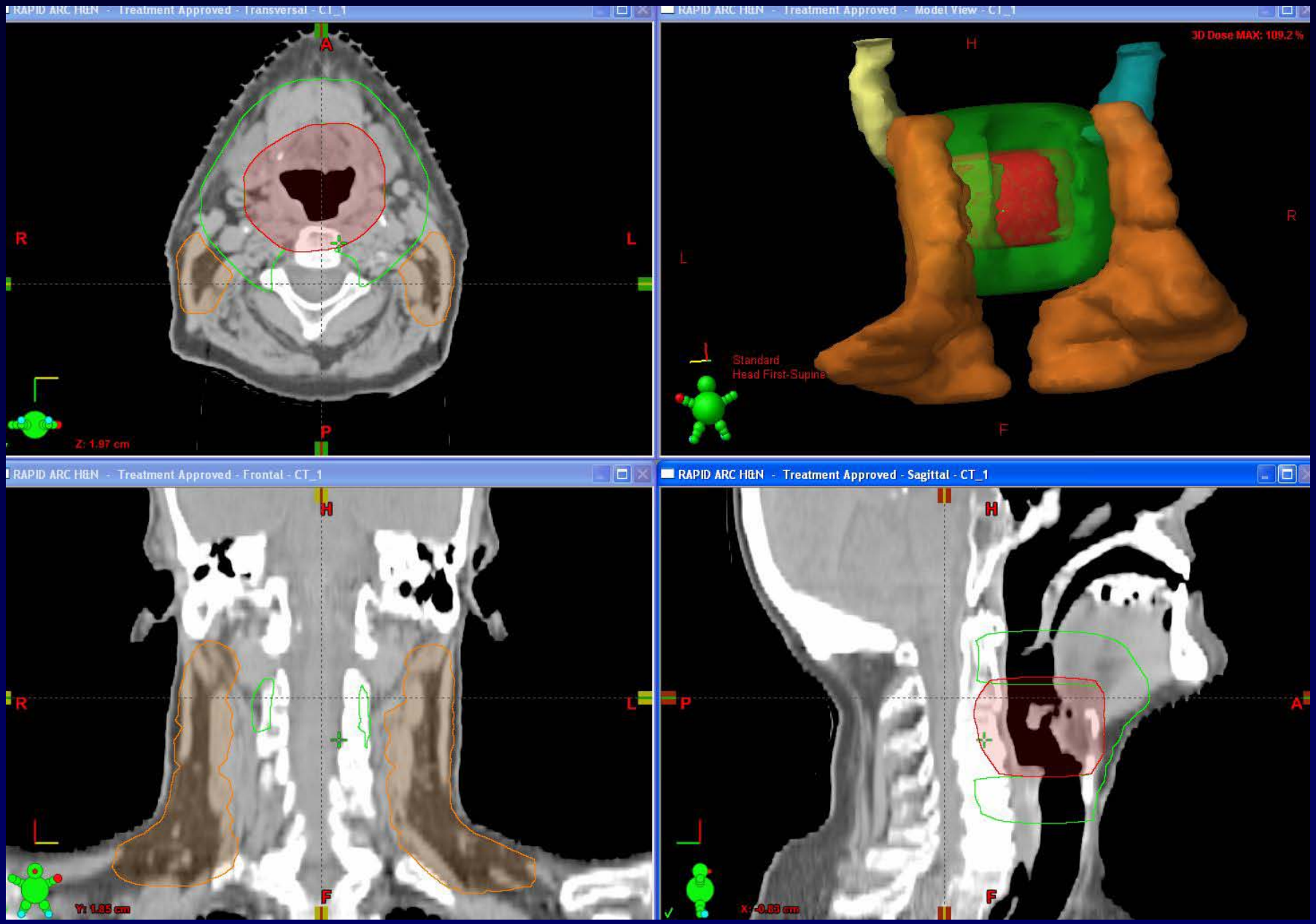


Not allowed



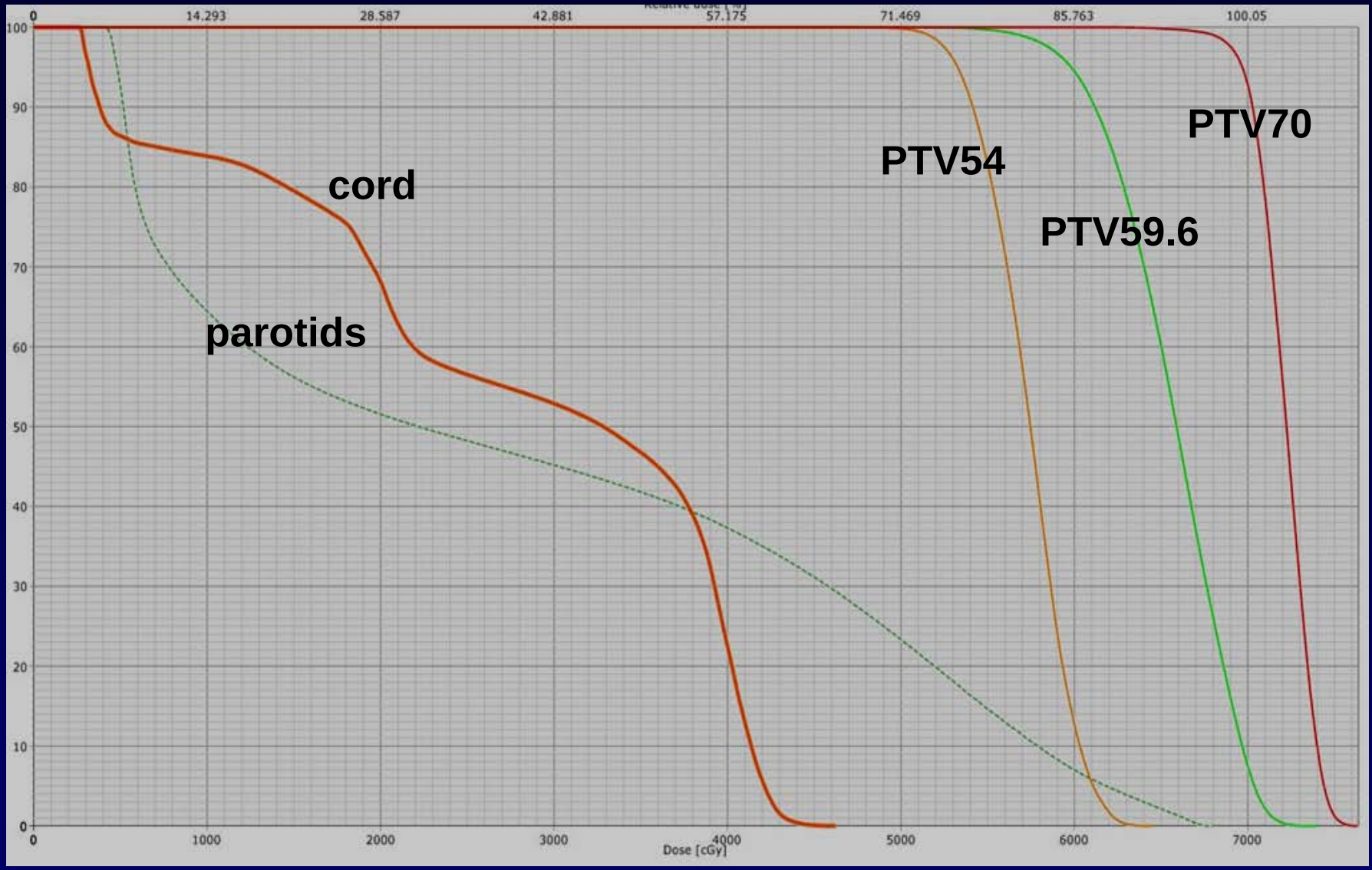
- Prostate and seminal vesicles plotted with 97% iso-cloud.
- 1 arc, 652 MUs, 1.7 minute delivery

Courtesy of Shirley Small



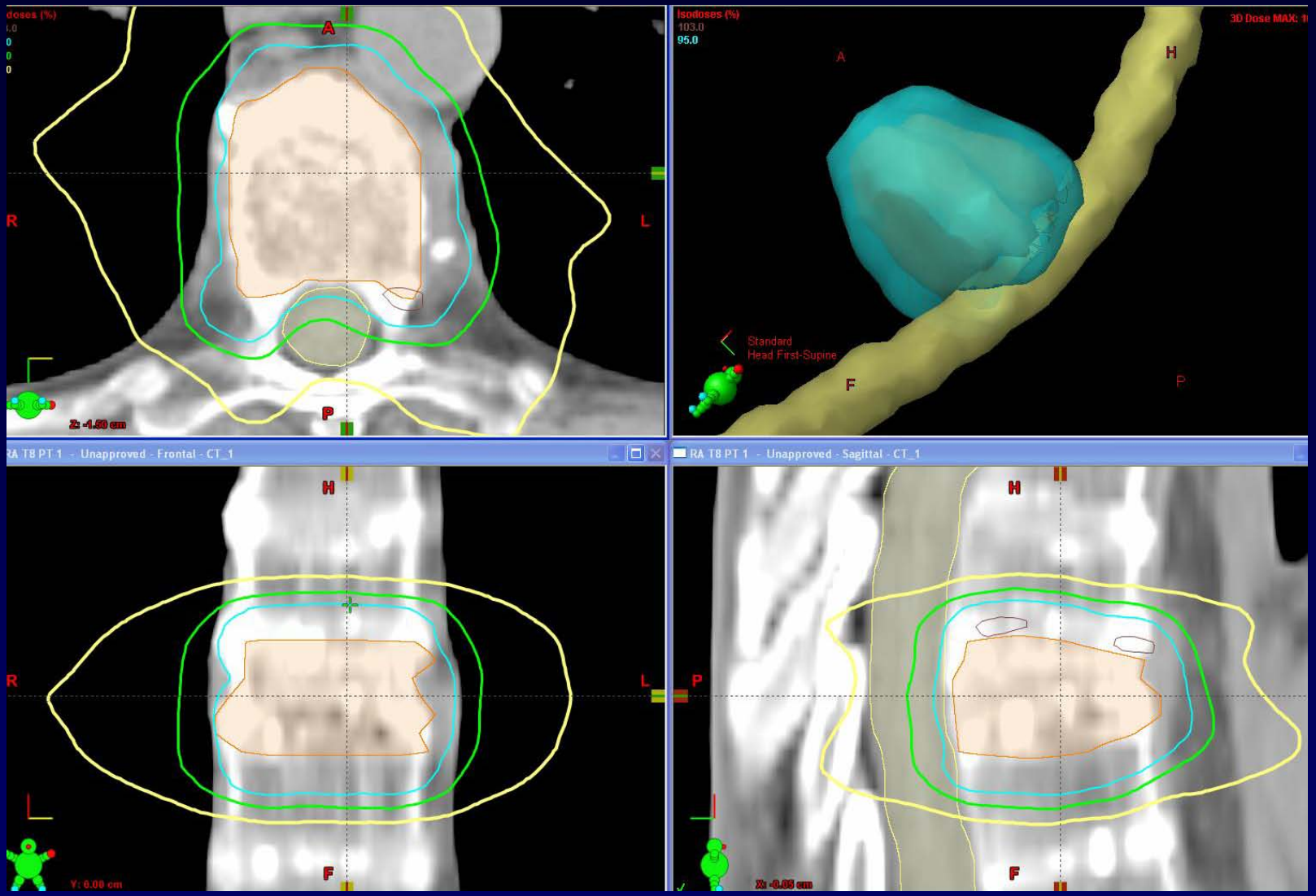
- H&N prescription levels of 54, 59.6, and 70 Gy

Courtesy of Shirley Small



- 1 arc, treatment time ≈ 2 minutes

Courtesy of Shirley Small



- Spine SBRT, 2 arcs, 4 minute delivery
- 95, 80, 50% isodose lines

Courtesy of Shirley Small

Monaco VMAT

Monaco Background (1)

- Markus Alber, a researcher at the University of Tübingen developed a treatment planning system called Hyperion.
- Two key feature of Hyperion are: (1) Monte Carlo based dose calculation and (2) Biology based IMRT optimization.
- Computerized Medical Systems (CMS) licensed the Hyperion system and created a commercial version called Monaco.

Monaco Background (2)

- Monaco 1.0 was released July 2007 as an IMRT-only planning system.
- In 2008, Elekta acquired CMS and began work to put a VMAT inverse planning solution into Monaco.
- Beta versions of the VMAT solution shipped in spring of 2010.

Monaco VMAT Algorithm

- First optimized fluence maps are produced at a series of discrete beam angles.
- These optimized fluence are then converted into deliverable VMAT arcs.

Monaco – Sweeping Window

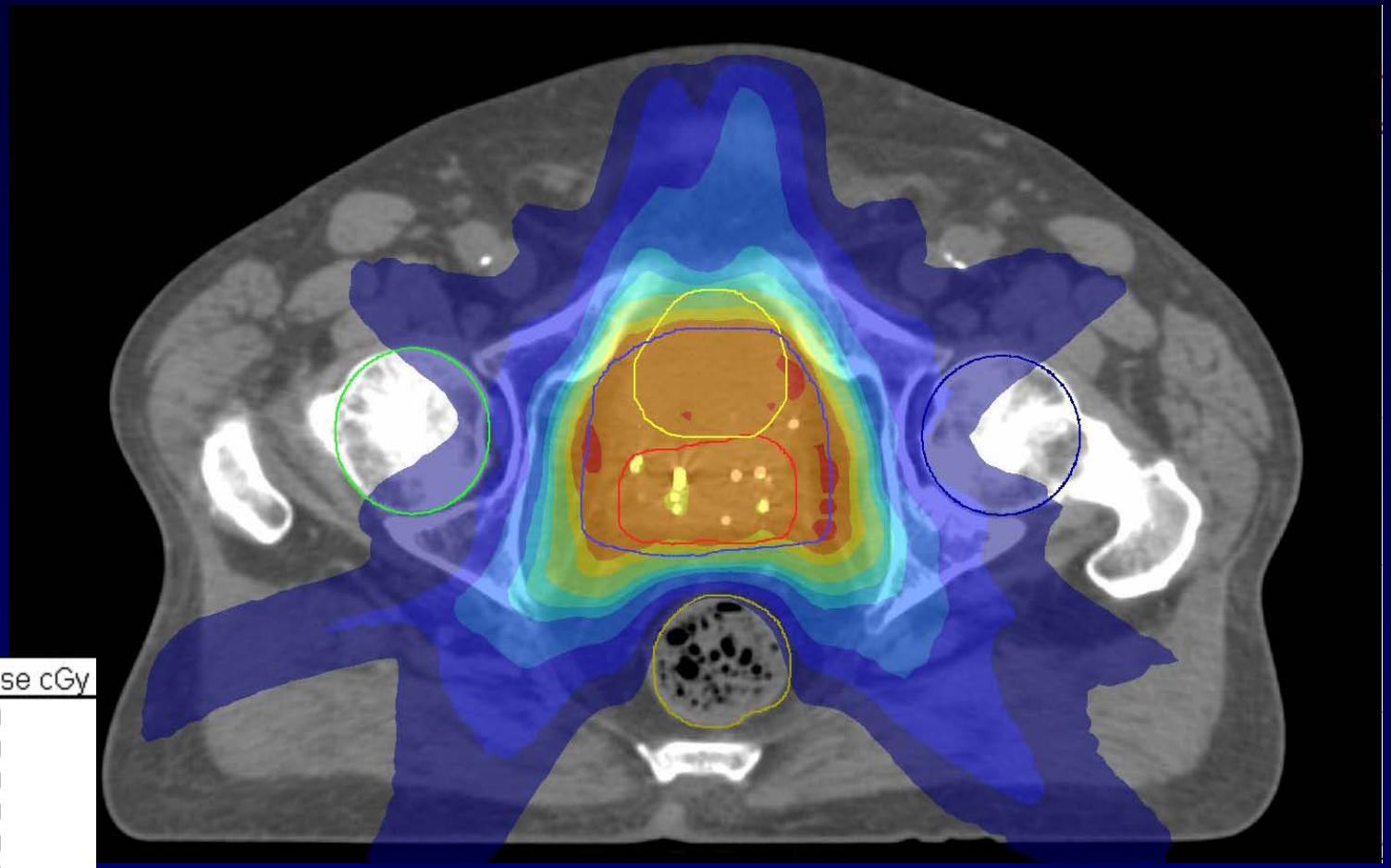
- Monaco produces plans using a “sweeping leaf sequencer” where the leaves move unidirectionally across the field.
- The leaf movement continues to alternate between sectors of the arc.

Sweeping-window arc therapy: an implementation of rotational IMRT with automatic beam-weight calculation

C Cameron 2005 *Phys. Med. Biol.* **50** 4317-4336 doi: 10.1088/0031-9155/50/18/006 Help

Monaco VMAT

Case #2 - Prostate

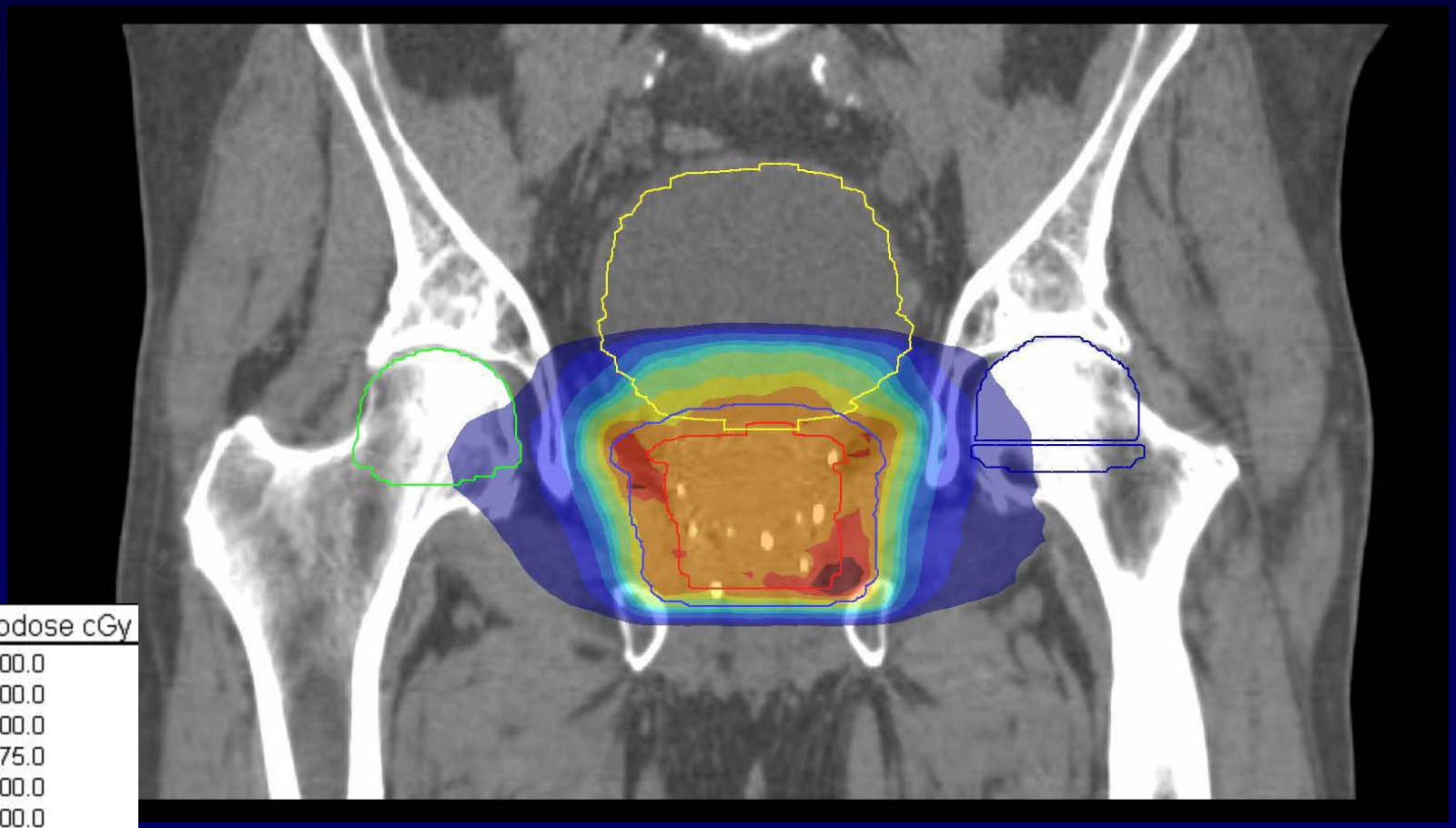


Color	Isodose cGy
	4800.0
	4700.0
	4500.0
	4275.0
	3800.0
	3500.0
	3200.0
	2550.0
	2000.0
	1500.0

- **180 cGy/fraction, 678 MU**
- **Delivery time = 3 min 54 sec**

Monaco VMAT

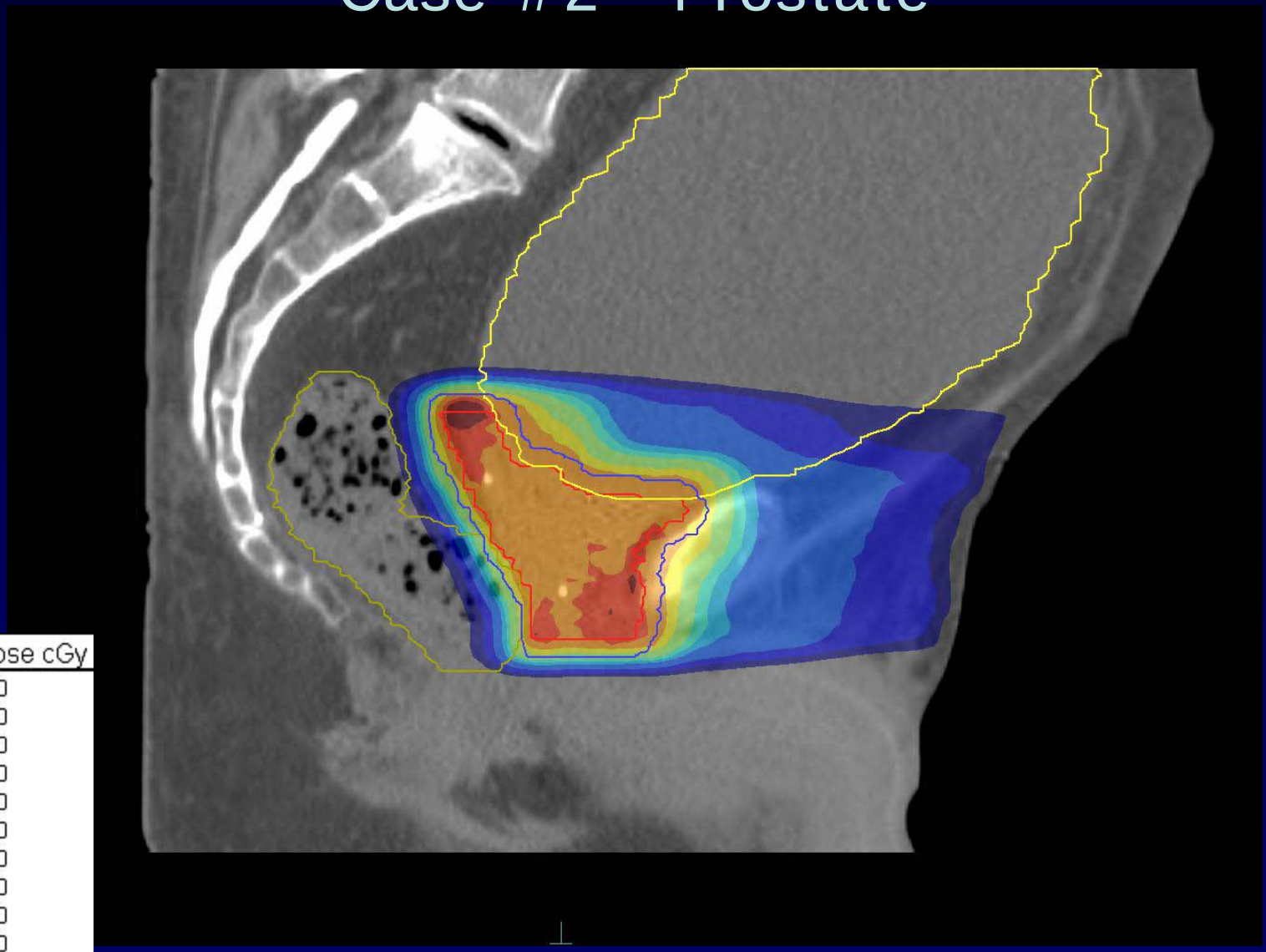
Case #2 - Prostate

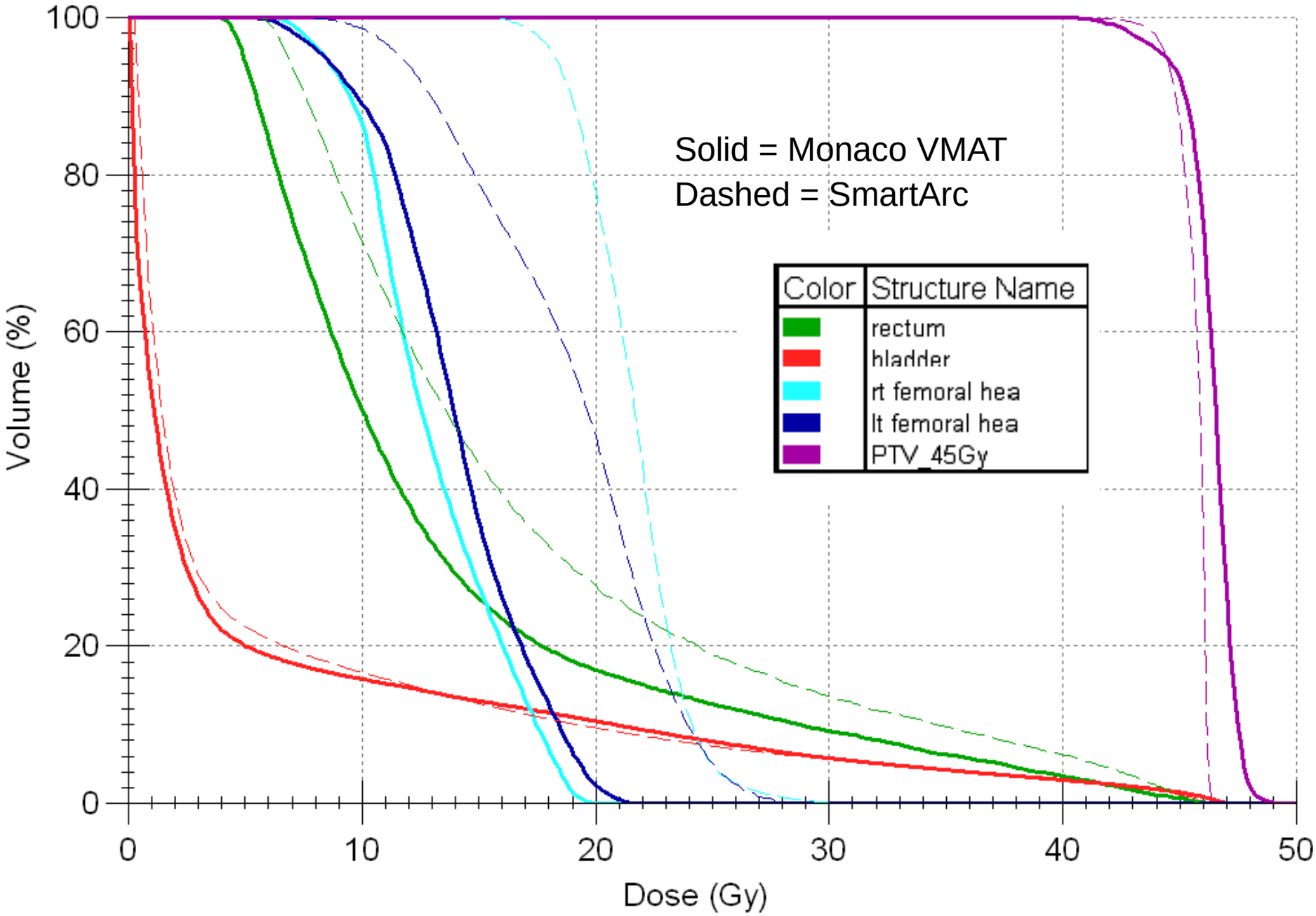


Color	Isodose cGy
	4800.0
	4700.0
	4500.0
	4275.0
	3800.0
	3500.0
	3200.0
	2550.0
	2000.0
	1500.0

Monaco VMAT

Case #2 - Prostate




Solid = Monaco VMAT
Dashed = SmartArc
Color
Structure Name
rectum
bladder
rt femoral hea
lt femoral hea
PTV_45Gy
Volume (%)
100
80
60
40
20
0
0
10
20
30
40
50
Dose (Gy)

Monaco - Summary

- Monaco will serve as Elekta's VMAT planning solution.
- Monaco VMAT is in Beta testing.
- Initial results are promising, but it is unclear if Monaco VMAT works well for the most complex cases.

SWEDISH

Philips Pinnacle - SmartArc

- SmartArc is an extension of the DMPO planning functionality in Pinnacle.
- The SmartArc planning tools were developed by RaySearch (Stockholm).

SWEDISH

SmartArc Features

- Works with VMAT-capable Varian and Elekta linacs
- Plans can be created with constant or variable dose rates
- Single or multiple arcs covering 90 to 360°
- Dose objectives can be changed during optimization
- Coplanar or non-coplanar plans

Courtesy Kevin Reynolds

Summary of SmartArc Clinical Cases

- 30 patients treated covering a variety of treatment sites including lung, head-and-neck, liver, pancreas, esophagus, brain, and chest wall.
- 1 arc used in 19 cases
- 2 arcs used in 11 cases.
- Average delivery time: 1 arc cases = 1.9 minutes, 2 arc cases = 3.9 minutes.

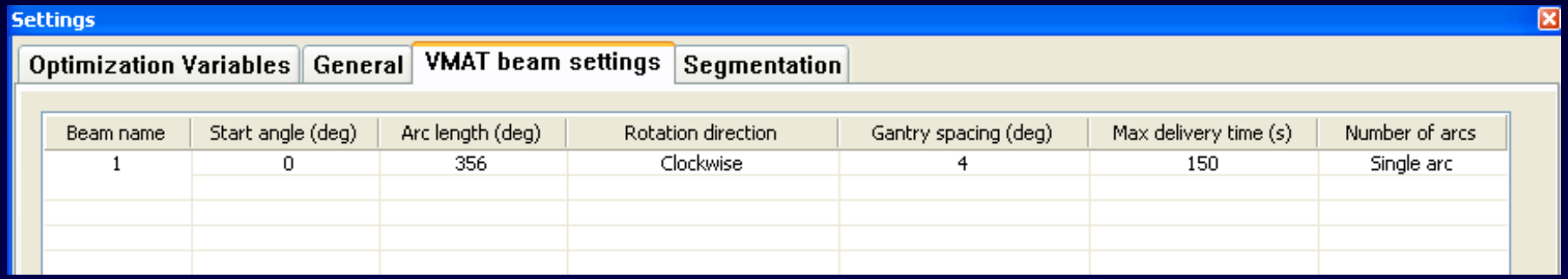
SWEDISH

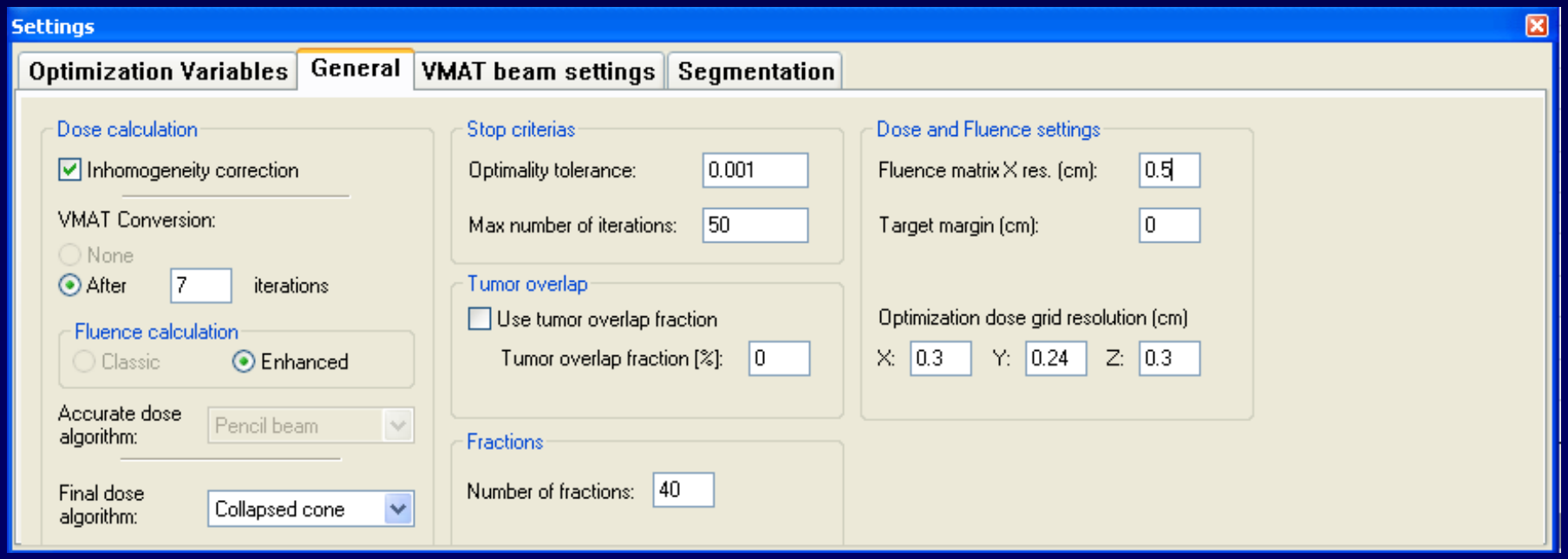
Nucletron – Oncentra VMAT

- The Oncentra VMAT module was developed by RaySearch Laboratories, a software development company located in Stockholm.
- RaySearch also developed the SmartArc module for Pinnacle.
- The underlying VMAT planning engine is the same.

SWEDISH

Nucletron – Oncentra VMAT





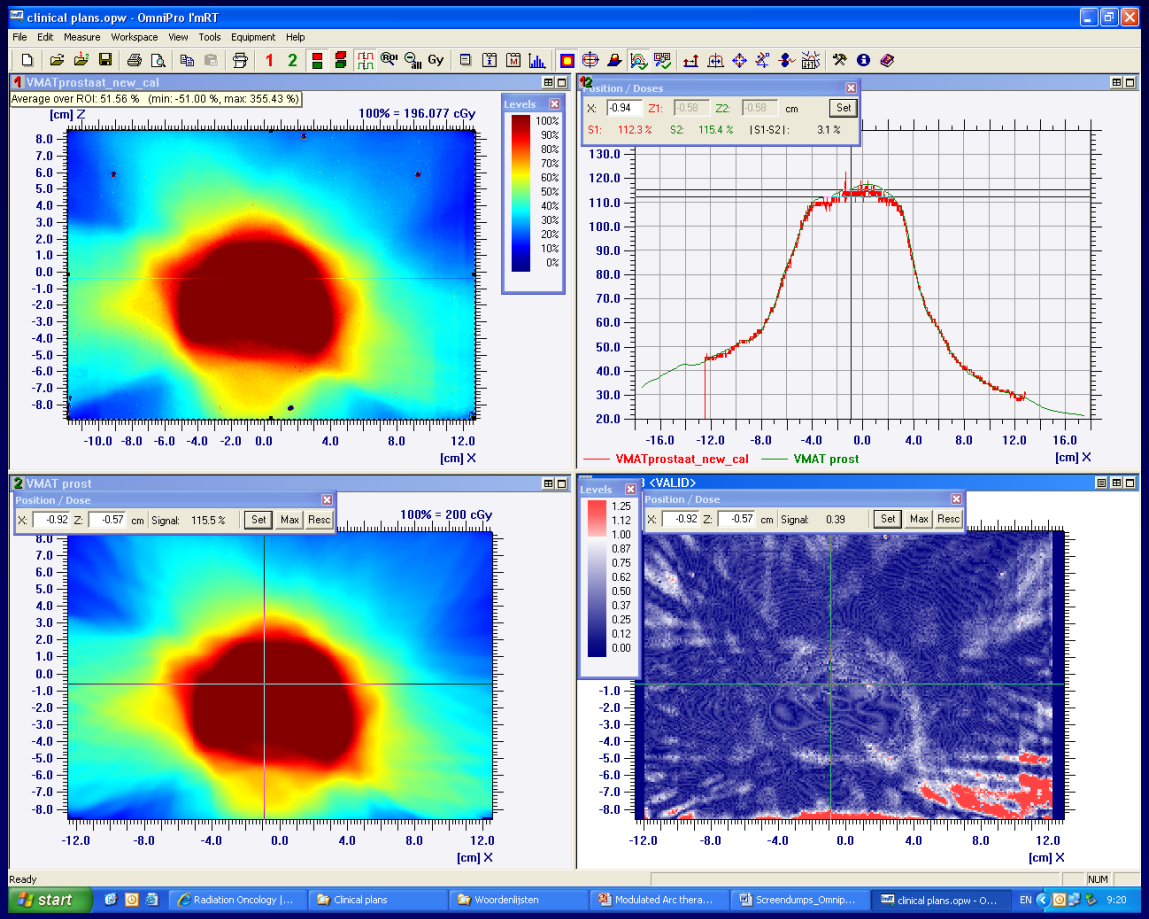
Prostate Verification

1-arc VMAT

γ(3%,1mm)

planned

measured



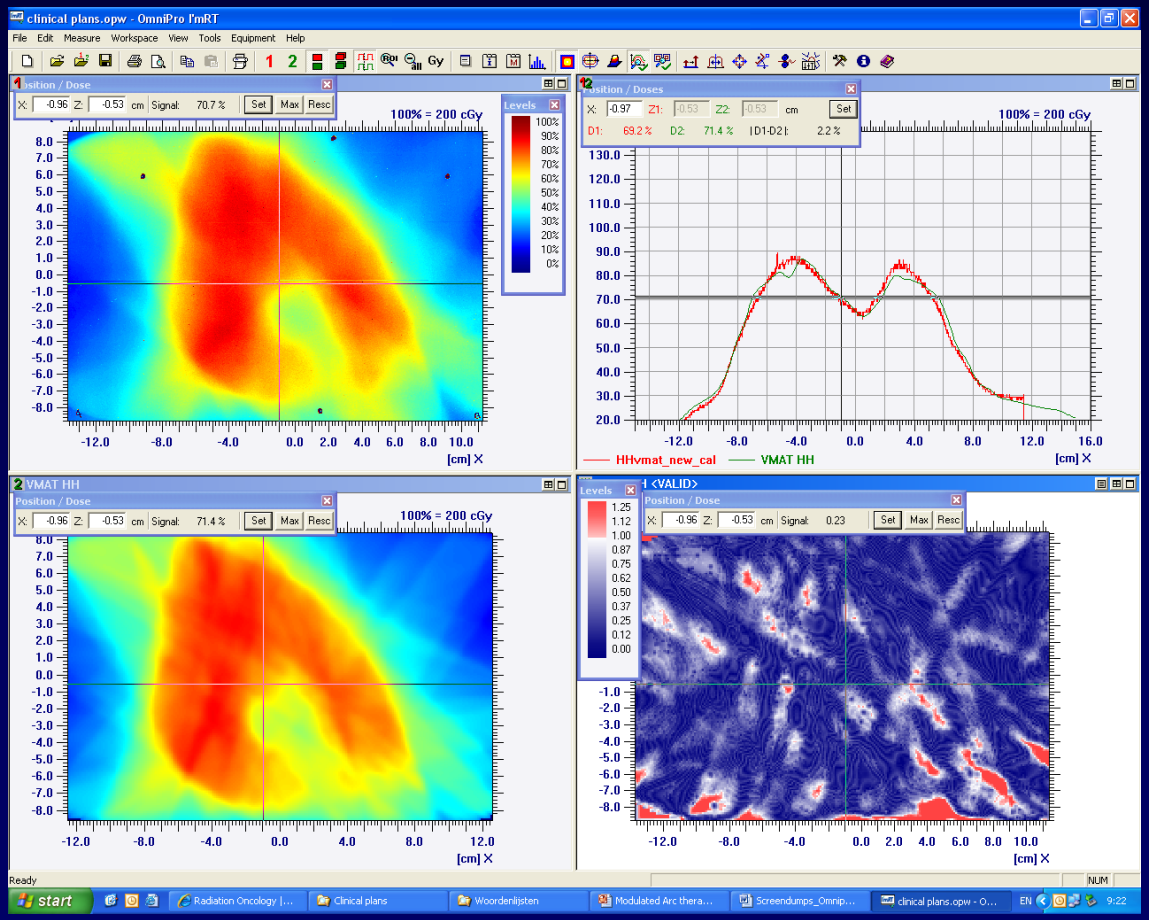
H&N Verification

VMAT

γ(3%,3mm)

planned

measured



Nucletron – Oncentra VMAT

- Oncentra VMAT was released in December 2009.
- 14 sites have been installed in Europe (non are clinical).
- No sites in the U.S. at this time.

SWEDISH

Siemens/Prowess CBT

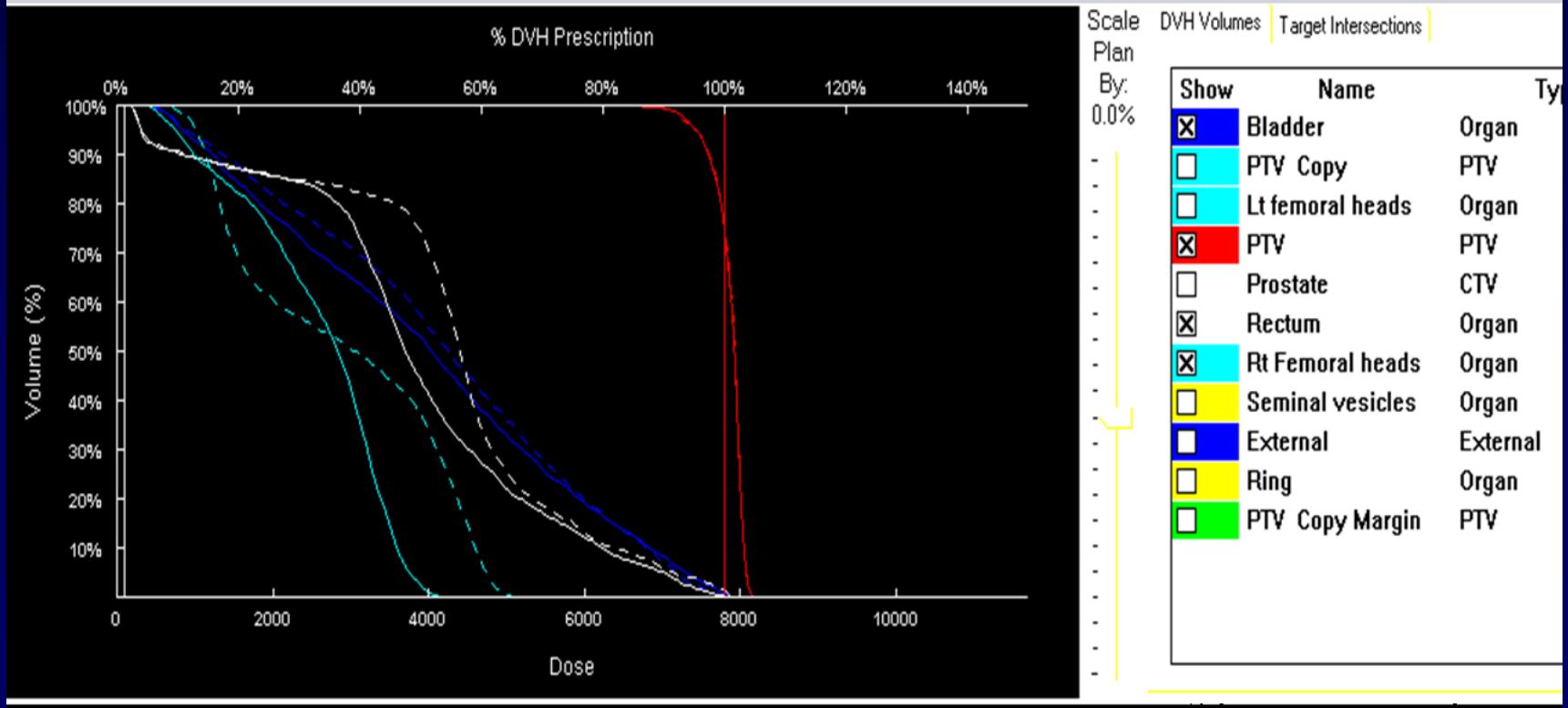
- Prowess' Direct Aperture Optimization algorithm is used to develop VMAT plans for delivery on Siemens linacs.

SWEDISH

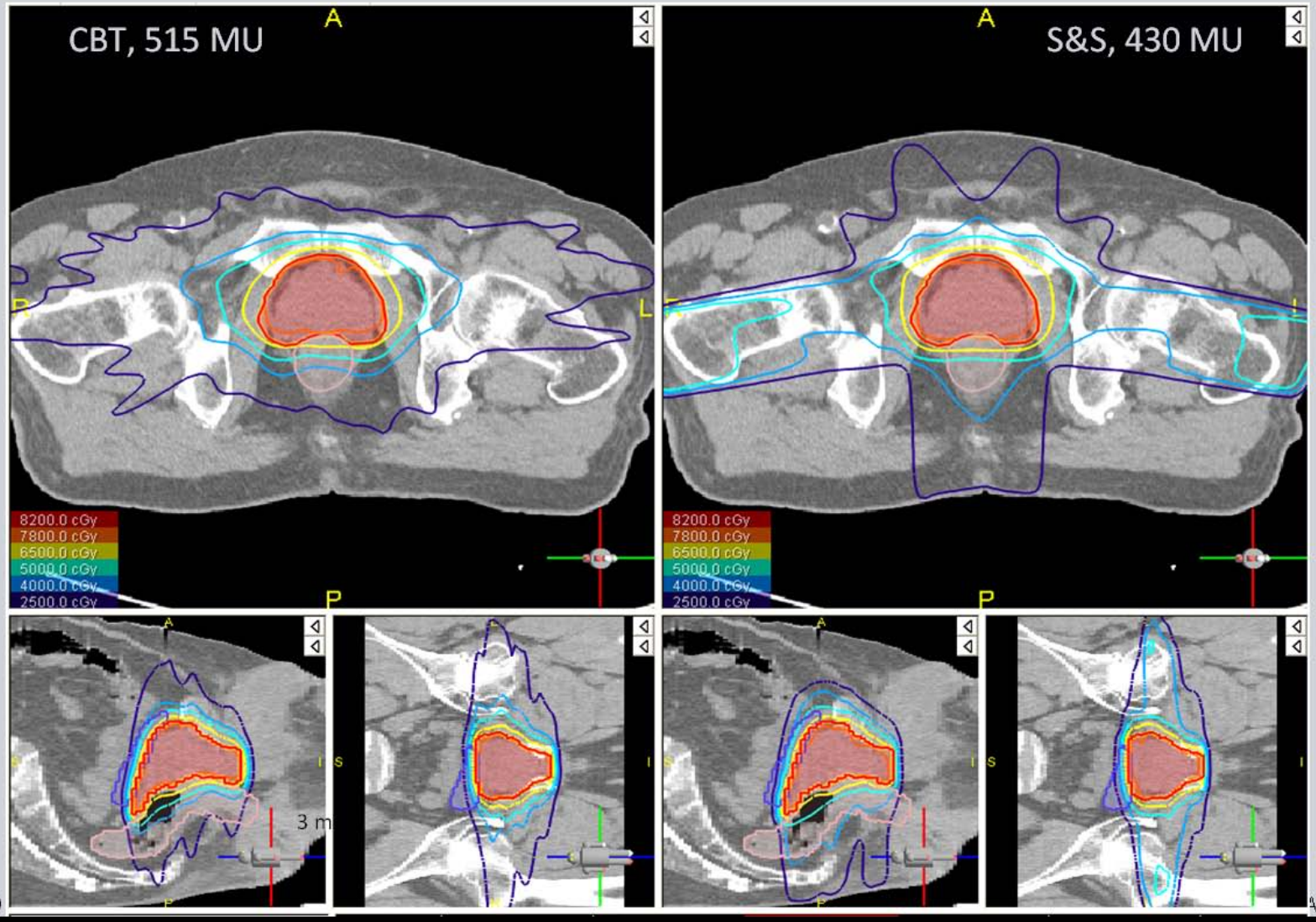
SIEMENS

Prostate IMRT (S&S and CBT) – MCW case 6/2009

- Step&Shoot IMRT (DAO) (dashed), and CBT (solid)
- S&S : 430 MU, 5 beams, 5 segments/beam
- CBT : 515 MU, 9 -29 MU/OP, nominal gantry speed ~2 deg/s



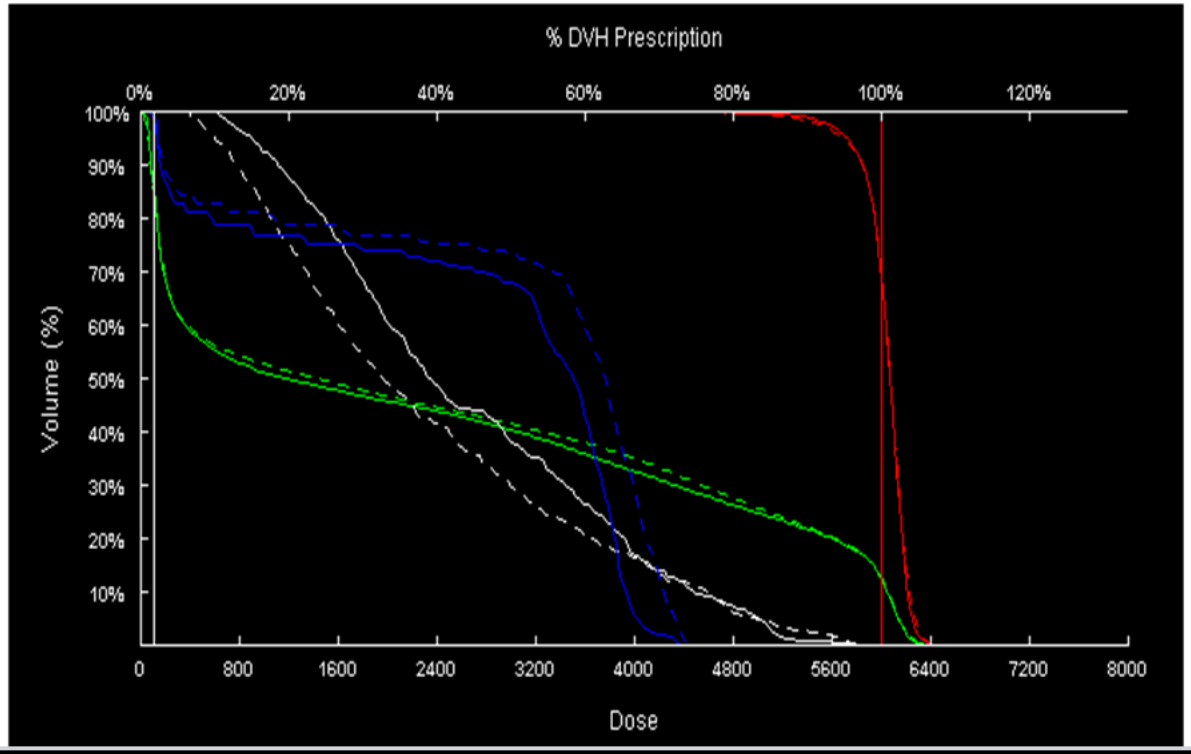
SIEMENS

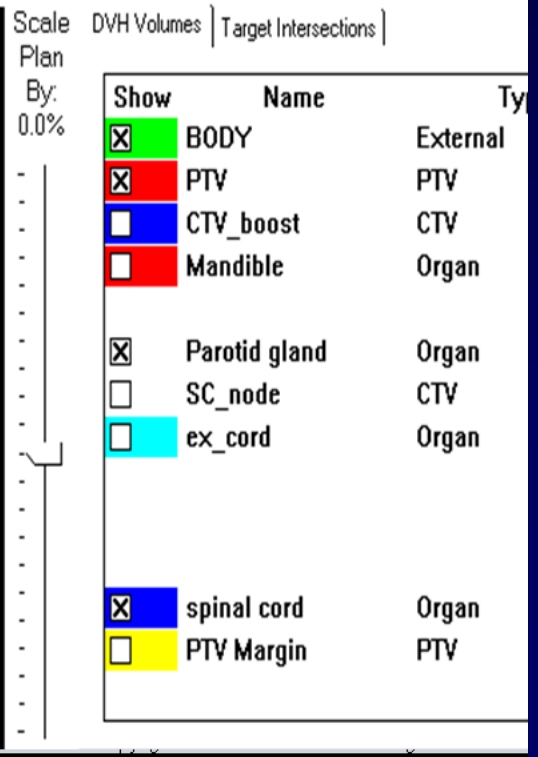


SIEMENS

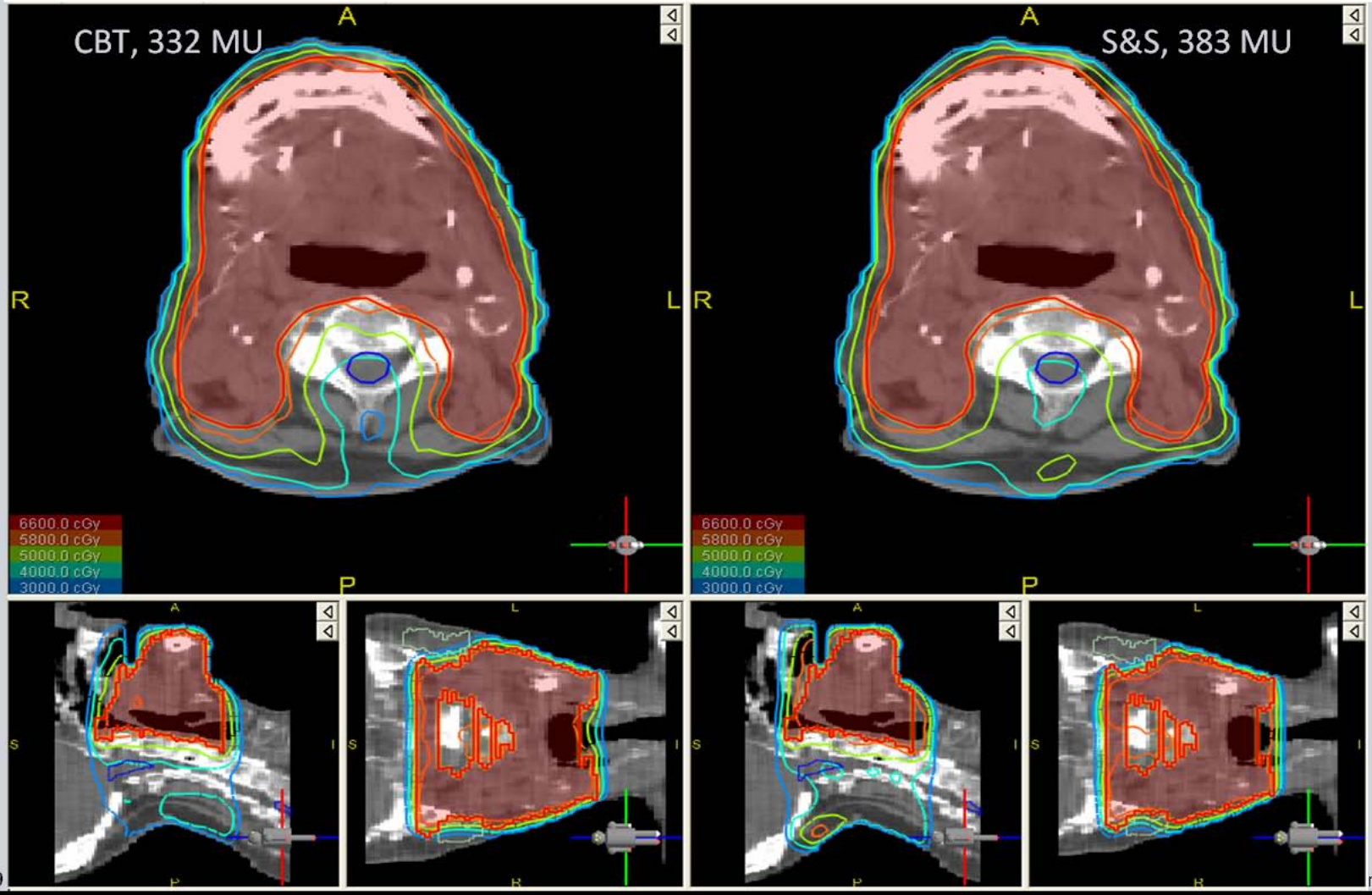
Prowess H&N IMRT (S&S and CBT) – MCW case 6/2009

- Step&Shoot IMRT (DAO) (dashed), and CBT (solid)
- S&S : 383 MU, 7 beams, 5 segments/beam
- CBT : 332 MU, 3-15 MU/OP, nominal gantry speed ~1.5 deg/s



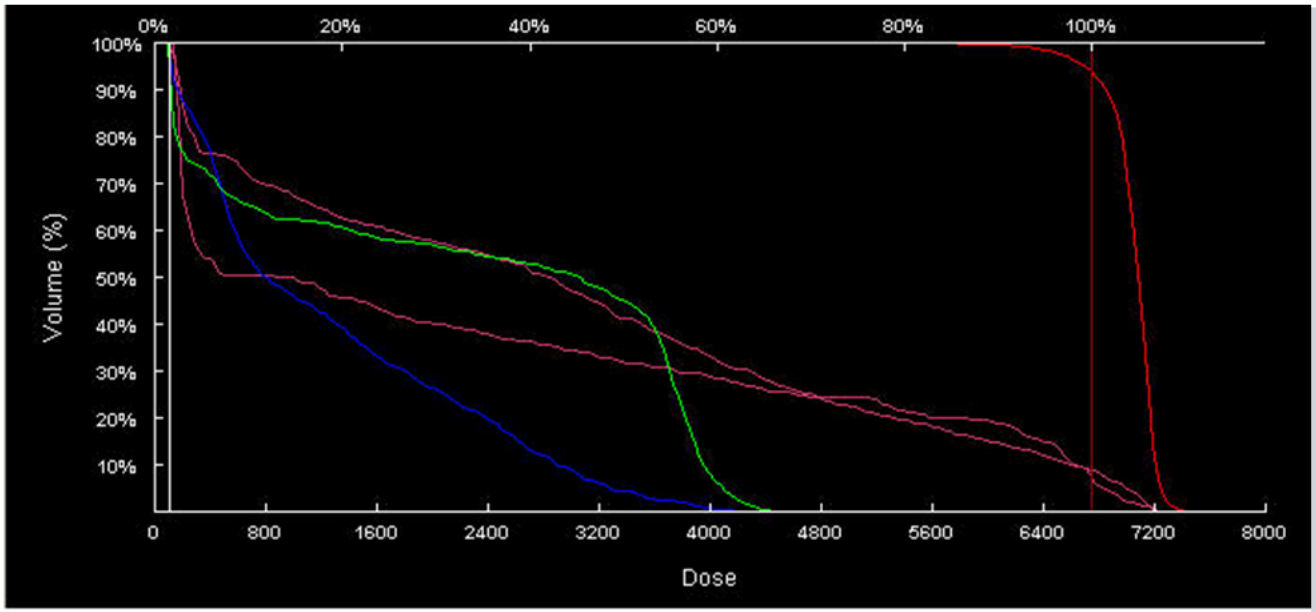


SIEMENS



SIEMENS

H&N CBT – RTOG IMRT criteria - U.Utah 8/2009



Histogram Mode
- (•) Integrated
- ( ) Differential

Histogram Background
- ( ) White
- [ ] Grid
- (•) Black

DVH Prescription 6750.00 cGy

Dose Plot Max 8000.00 cGy

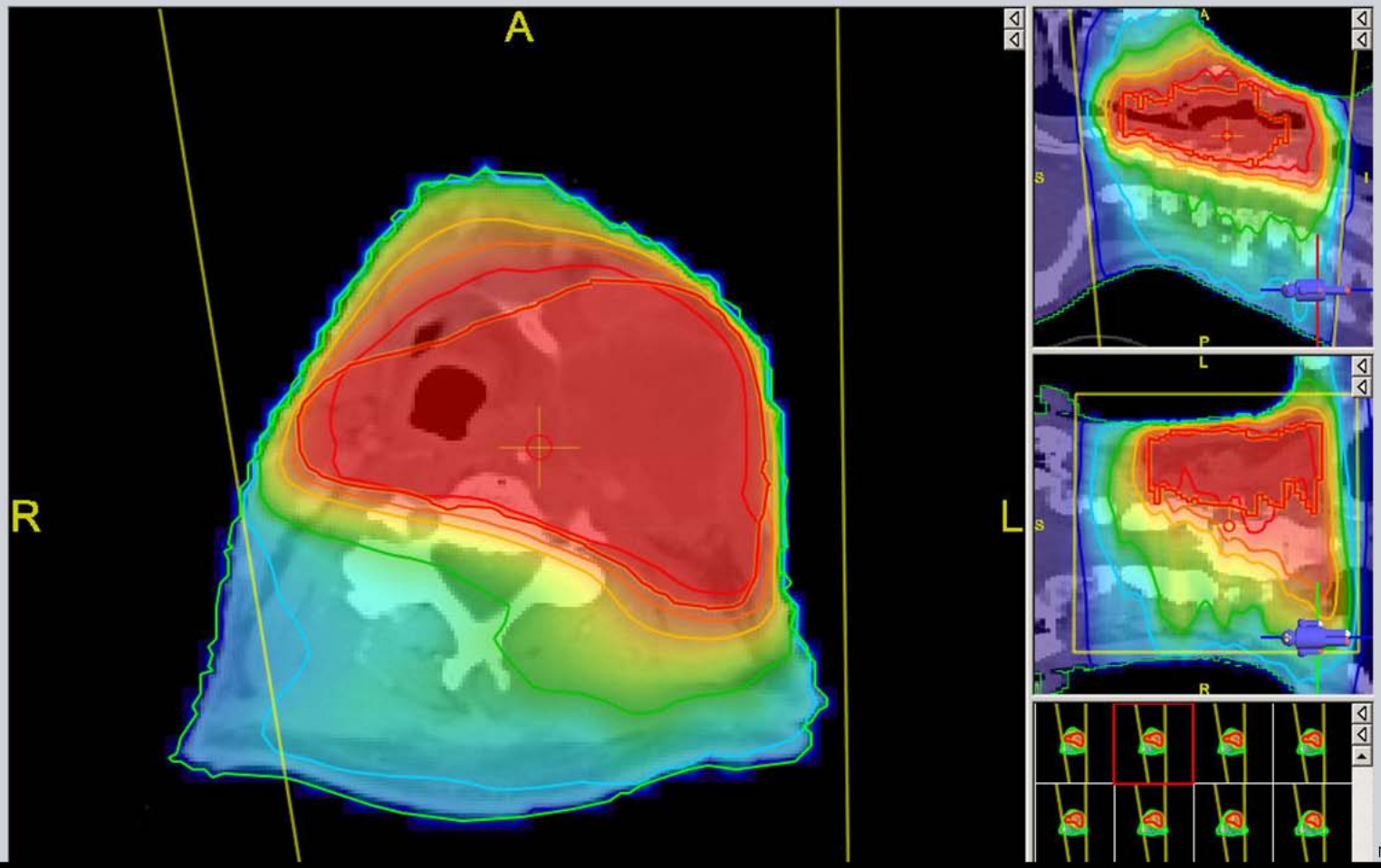
Compare Plan
- Model: CT_2
- Plan: –none–

Name	Vol	DLV (%)	D-X (cGy)			V-X (%)			Min	Max
	[cc]	100.0	100	90	80	150	100	90	[cGy]	[cGy]
Esophagus	15.5	100.0	150.2	126.9	178.9	0.0	6.2	18.9	146.5	7208.0
Lt Parotid	35.8	99.3	112.7	174.8	295.4	0.0	8.7	14.5	96.7	7188.4
PTV 1	485.9	100.0	4920.4	6801.0	6918.2	0.0	93.1	99.5	4901.1	7512.0
Rt Parotid	34.0	95.9	112.7	119.2	305.4	0.0	0.0	0.0	79.1	4172.8
Spinal Cord	29.5	94.4	112.7	91.5	127.2	0.0	0.0	0.0	97.0	4439.7

SIEMENS

CBT H&N – Prowess - U.Utah 8/2009

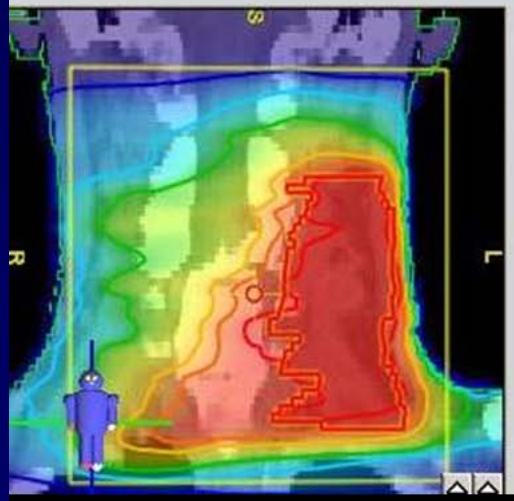
- H&N

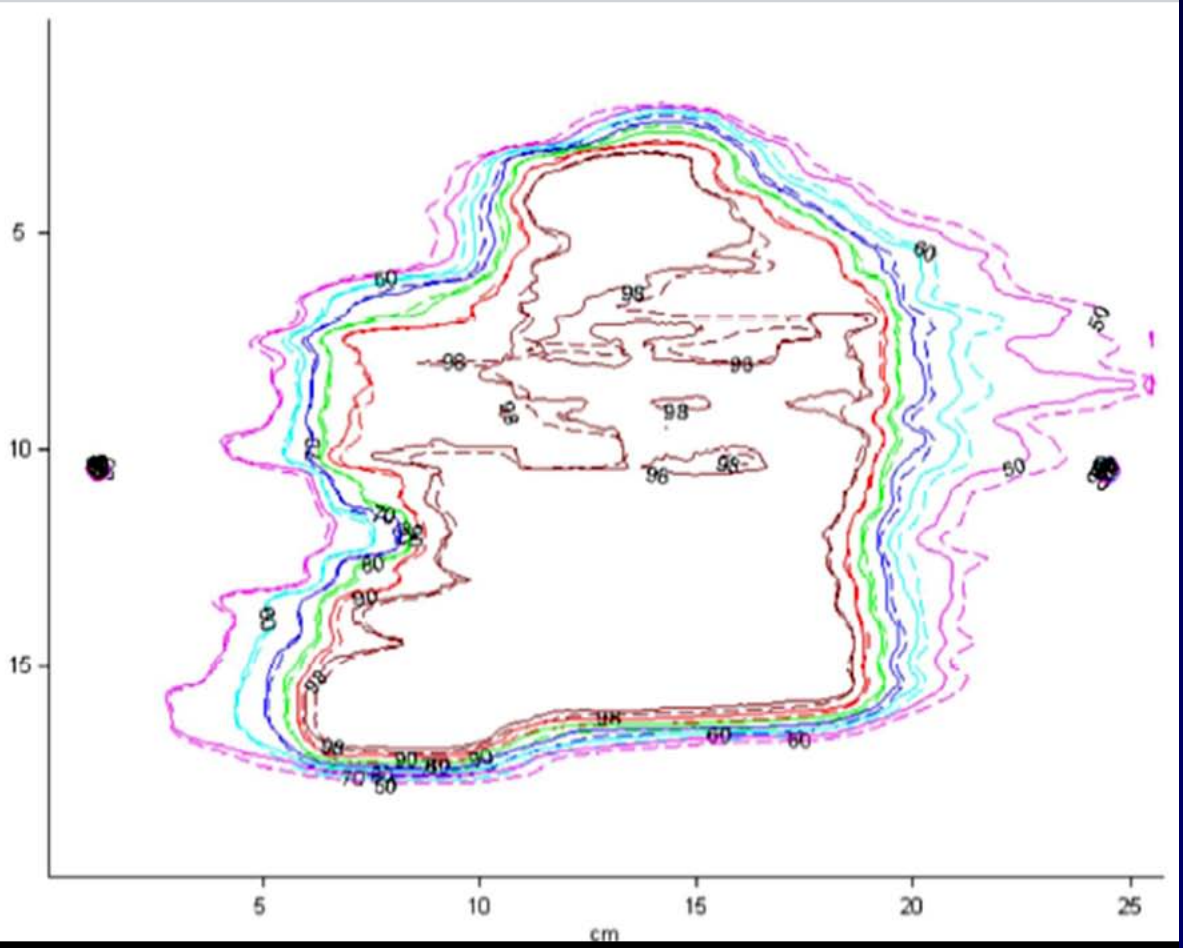


SIEMENS

CBT H&N – Prowess - U.Utah 8/2009

- Gamma – Calculated versus Film measurement to Phantom – 96%passrate [3%,4mm]
- Actual delivery time
  - ~3½ min.





Objectives/Constraints used in Radiation Therapy

- Dosimetric Objective Functions/Constraints
  - Definition
  - Possible objective functions
  - Possible constraints
  - Advantages and disadvantages
- Biological Objective Functions/Constraints
  - Definition
  - Possible objective functions
  - Possible constraints
  - Advantages and disadvantages

Is it robust?

- “A system that holds up well under exceptional conditions.”
- Does it work well for tumors of any size and shape?
- Can it avoid local minima?
- Does it produce efficient plans?

Is it flexible?

- Each physician will have his or her personal preferences as to what constitutes an “optimal” plan.

Is it fast?

- IMRT treatment planning is an iterative approach typically requiring multiple optimizations.
- Can you interact real-time during the IMRT optimization?

Current IMRT optimization ("inverse planning"), *single* score

IMRT optimization finds the plan that yields the best score *F* while considering given constraints

$$F = w_{\text{Target}} \cdot F_{\text{Target}} + w_{\text{Risk1}} \cdot F_{\text{Risk1}} + w_{\text{Risk2}} \cdot F_{\text{Risk2}} + \ldots$$

objectives, costlets, indicators

weights, penalties, importance factors

Note: *F* is a single number (grade, score)!

Courtesy of Thomas Bortfeld

Three steps of multi-criteria Pareto IMRT optimization (MCO):

1. Setting the planning “horizon”
2. Calculating the Pareto surface
3. Interactive plan navigation

Courtesy of Thomas Bortfeld

Comparison with Beamlet-based Inverse Planning

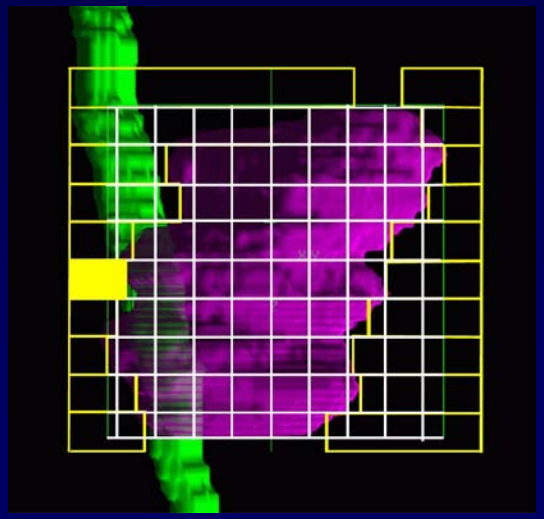
- DAO reduced the number of segments by up to 95%.
- DAO reduced MU by up to 80%.
- Note: Results specific to Elekta and Corvus.

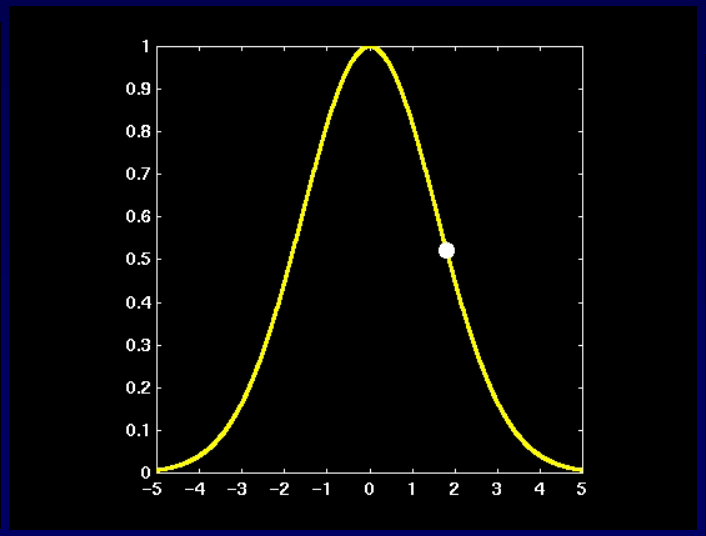
Simulated annealing optimization

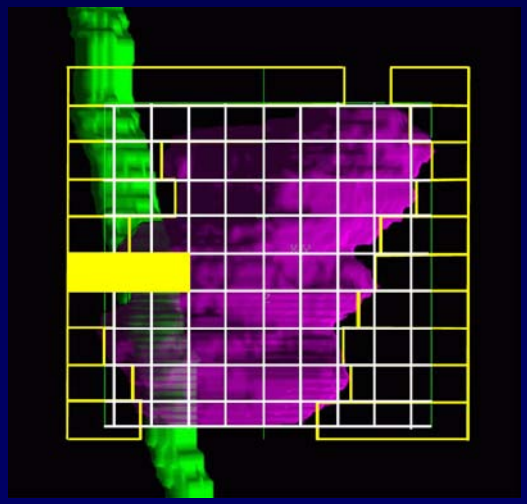
Pick a parameter: (eg. 5th leaf of 4th angle in 2nd arc)

Sample size of change from a Gaussian distribution

Make the change

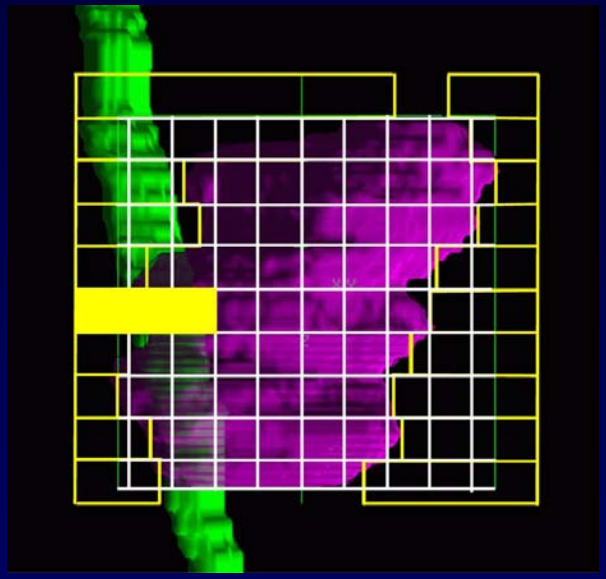






Delivery constraints

Does this change satisfy the delivery constraints?



Yes: Calculate new dose based on this change and compute the objective function

No: Immediately reject change and select a new change

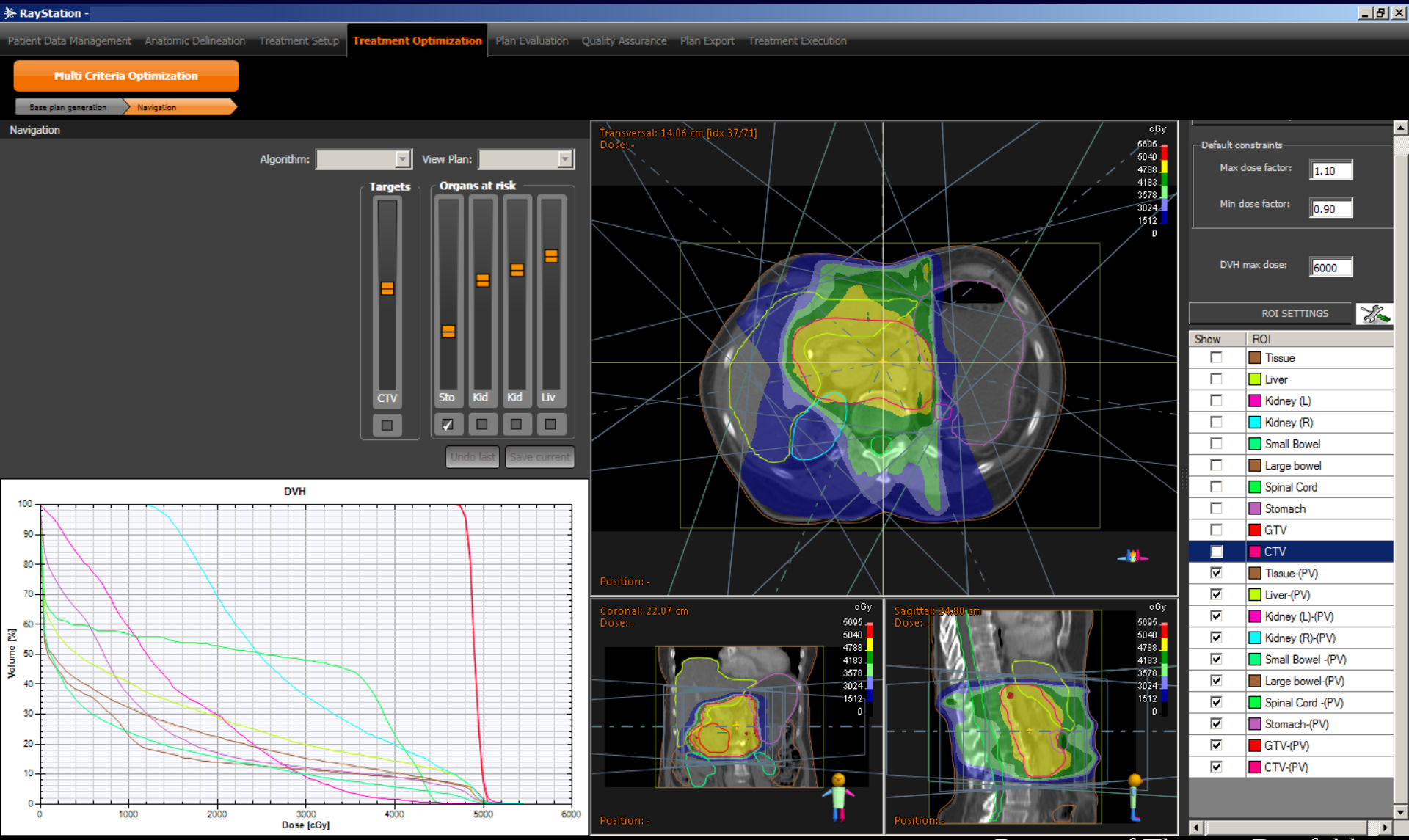
Comparison with Beamlet-based Inverse Planning

- A direct comparison was made between DAO and Corvus for four clinical cases.
- In each case, we sought equivalent treatment plan quality.

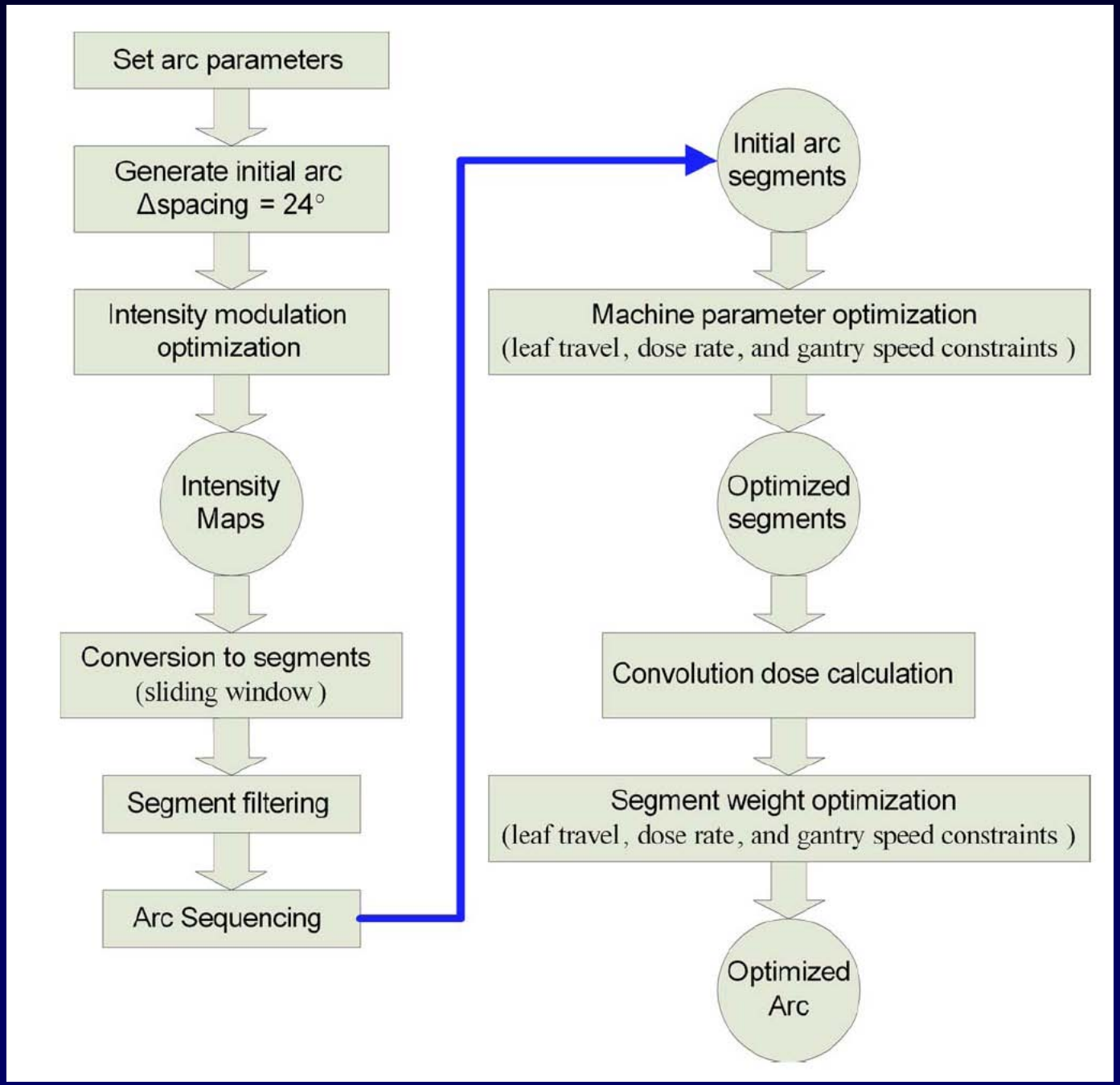
RaySearch MCO prototype

Courtesy of Thomas Bortfeld

RaySearch MCO prototype



Courtesy of Thomas Bortfeld



Courtesy of Philips Medical

Direct aperture optimization: A turnkey solution for step-and-shoot IMRT

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IMRT treatment plans for step-and-shoot delivery have traditionally been produced through the optimization of intensity distributions (or maps) for each beam angle. The optimization step is followed by the application of a leaf-sequencing algorithm that translates each intensity map into a set of deliverable aperture shapes. In this article, we introduce an automated planning system in which we bypass the traditional intensity optimization, and instead directly optimize the shapes and the weights of the apertures. We call this approach "direct aperture optimization." This technique allows the user to specify the maximum number of apertures per beam direction, and hence provides significant control over the complexity of the treatment delivery. This is possible because the machine dependent delivery constraints imposed by the MLC are enforced within the aperture optimization algorithm rather than in a separate leaf-sequencing step. The leaf settings and the aperture intensities are optimized simultaneously using a simulated annealing algorithm. We have tested direct aperture optimization on a variety of patient cases using the EGS4/BEAM Monte Carlo package for our dose calculation engine. The results demonstrate that direct aperture optimization can produce highly conformal step-and-shoot treatment plans using only three to five apertures per beam direction. As compared with traditional optimization strategies, our studies demonstrate that direct aperture optimization can result in a significant reduction in both the number of beam segments and the number of monitor units. Direct aperture optimization therefore produces highly efficient treatment deliveries that maintain the full dosimetric benefits of IMRT. [DOI: 10.1118/1.1477415]

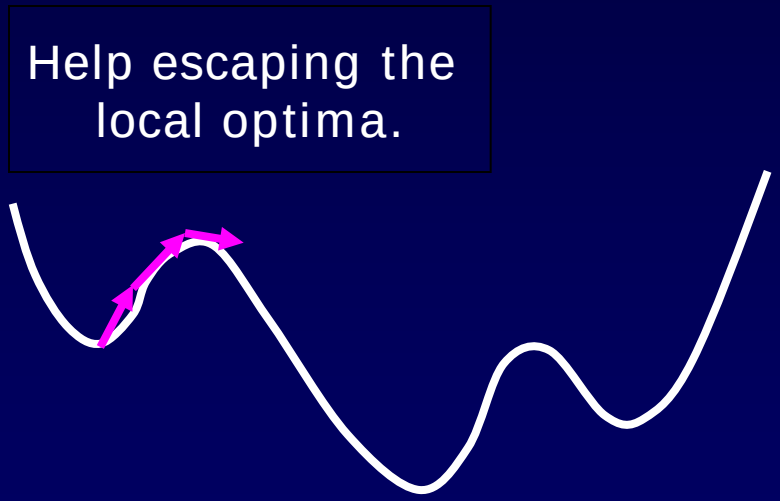
Key words: IMRT, inverse treatment planning, optimization, intensity modulation

Simulated Annealing (1)

- DAO uses simulated annealing, an optimization technique using random sampling techniques.
- The term simulated annealing derives from the roughly analogous physical process of heating and then slowly cooling a substance to obtain a strong crystalline structure.
- In each simulation, a minima of the cost function corresponds to this ground state of the substance.

Simulated Annealing (2)

- The basic principle is that by allowing occasional ascent in the search process, we might be able to escape the trap of local minima.



Comparison with Beamlet-based Inverse Planning

	Prostate	Pancreas	Head/neck
Corvus	348 seg. 2135 MU	588 seg. 2769 MU	216 seg. 1726 MU
P^3IMRT	72 seg. 552 MU	134 seg. 616 MU	118 seg. 737 MU
DAO	27 seg. 315 MU	18 seg. 365 MU	30 seg. 397 MU

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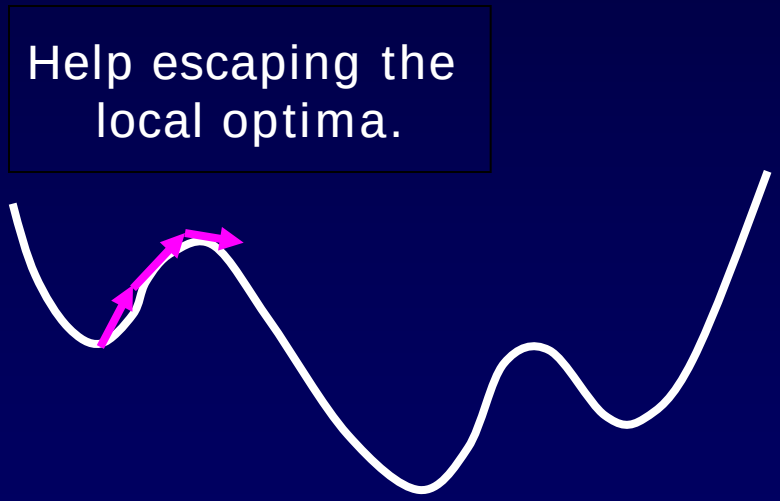


Simulated Annealing Objective/Constraints

- All linear and nonlinear objectives can be used.
- Highly nonlinear functions are not problematic.

Simulated Annealing - Advantages

- Easy to implement, no commercial software required.
- Provides significant flexibility in defining the problem.
- Able to escape local minima.

Simulated Annealing - Disadvantages

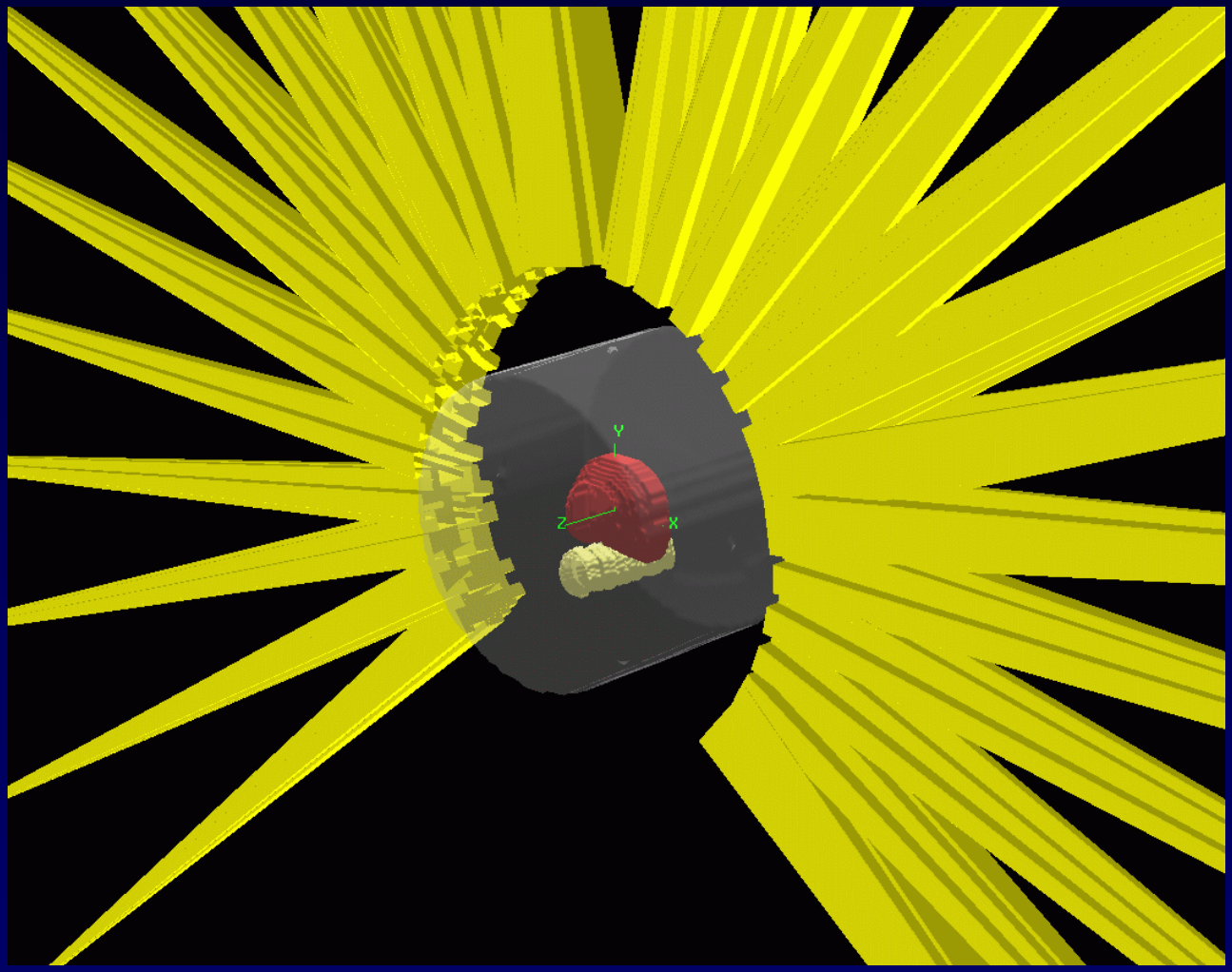
- Inefficient.

DAO Optimization

- A simulated annealing algorithm is used to optimize the MLC leaf positions and aperture weights.
- After each change in an MLC leaf position, the algorithm checks to see if any of the delivery constraints are violated. If so, the change is rejected.
- Otherwise, the change is accepted based on the rules of simulated annealing.

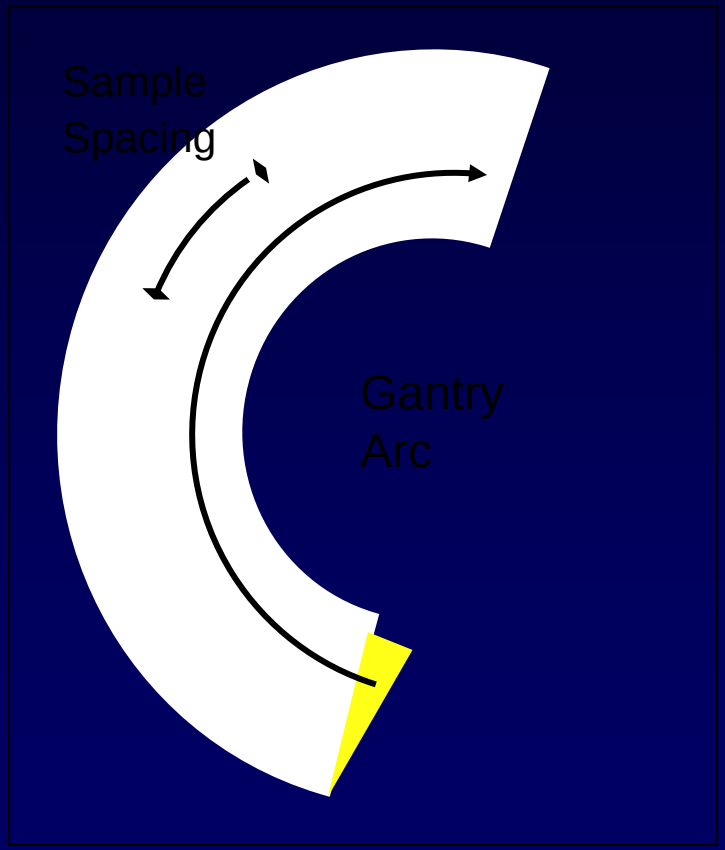
SWEDISH

In IMAT, an arc is approximated by a series of fixed beams.



Dynamic Source Model

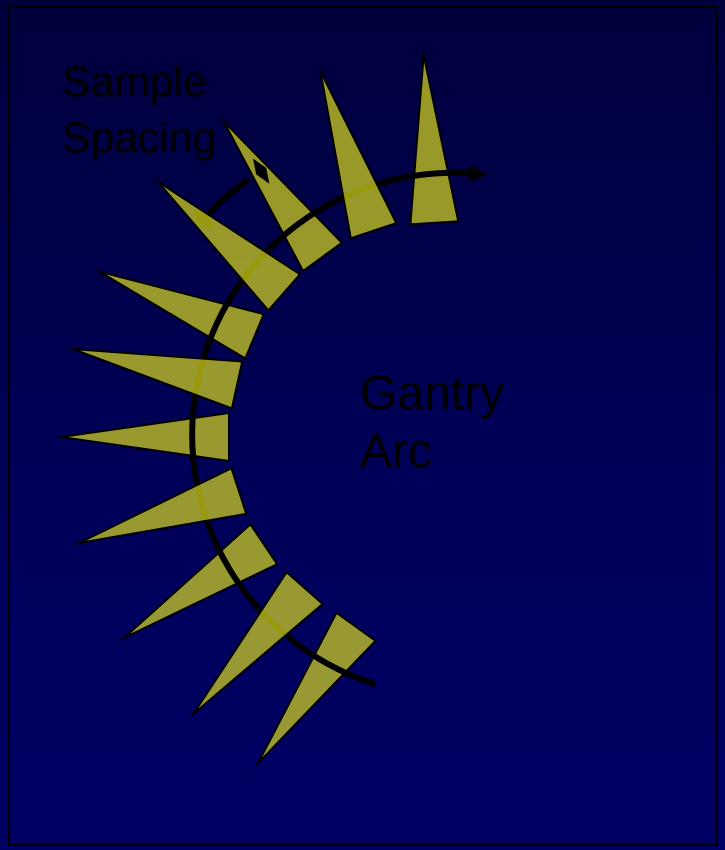
Sampling	Flexibility	Accuracy
Coarse	√	X



Courtesy of Karl Otto

Dynamic Source Model

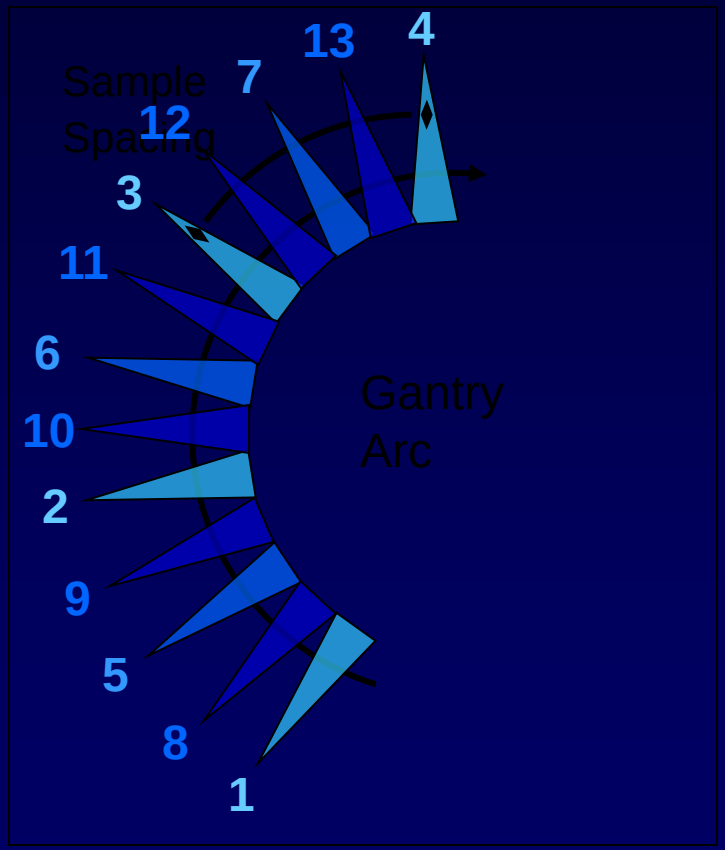
Sampling	Flexibility	Accuracy
Coarse	√	X
Fine	X	√



Courtesy of Karl Otto

Progressive Sampling

Sampling	Flexibility	Accuracy
Coarse	√	X
Fine	X	√
Progressive	√	√



Courtesy of Karl Otto

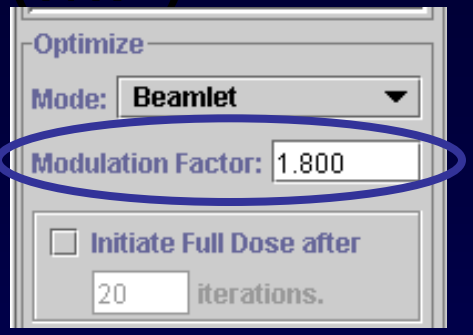
User Inputs:
Modulation Factor (MF)

- A balancing act between conformality and efficiency:
  - *Conformality:* If some beam angles are better than others for treating the target and avoiding sensitive structures, unequal weighting of beamlets can yield a better DVH.
  - *Efficiency:* The most efficient way to deliver all the dose is to weight all the beamlets equally because:
    - The gantry speed (which is constant for a given plan) must be slow enough to accommodate the longest beamlet open time in the plan.

User Inputs:
Modulation Factor (MF)

- The Modulation Factor limits the range of leaf-open times:

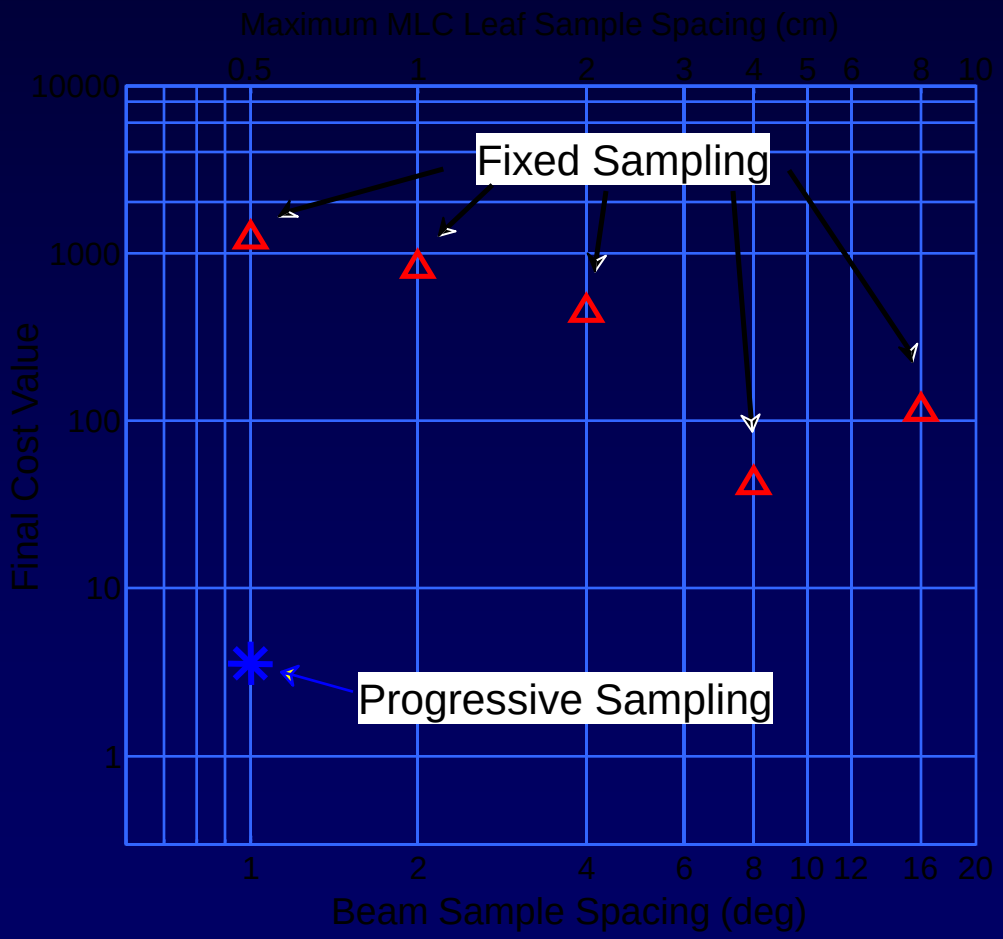
$$\text{Modulation Factor} = \left[\frac{\text{Max Open Time}}{\text{Avg Open Time}} \right]$$



- The user-defined MF sets an upper limit on the range of open times for "used" beamlets.
- Large MF's create plans with a large fraction of small leaf-open times, which have larger uncertainties.

- Typical MF's:
  - 1.8 for prostate
  - 2.4 for Head & Neck
- Increasing the MF:
  - Increases delivery time (generally linearly with MF)
  - Decreases efficiency
- Decreasing the MF may degrade dose conformity.

Progressive Sampling



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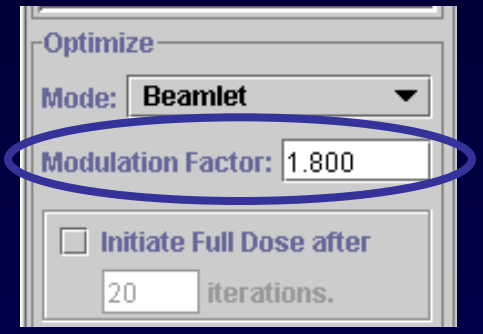

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TomoTherapy® Inverse Planning System