IMRT/VMAT: Theory and Definitions

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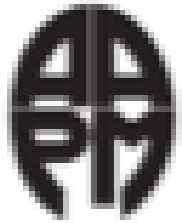
AAPM

ICTP 2019



Learning Objectives

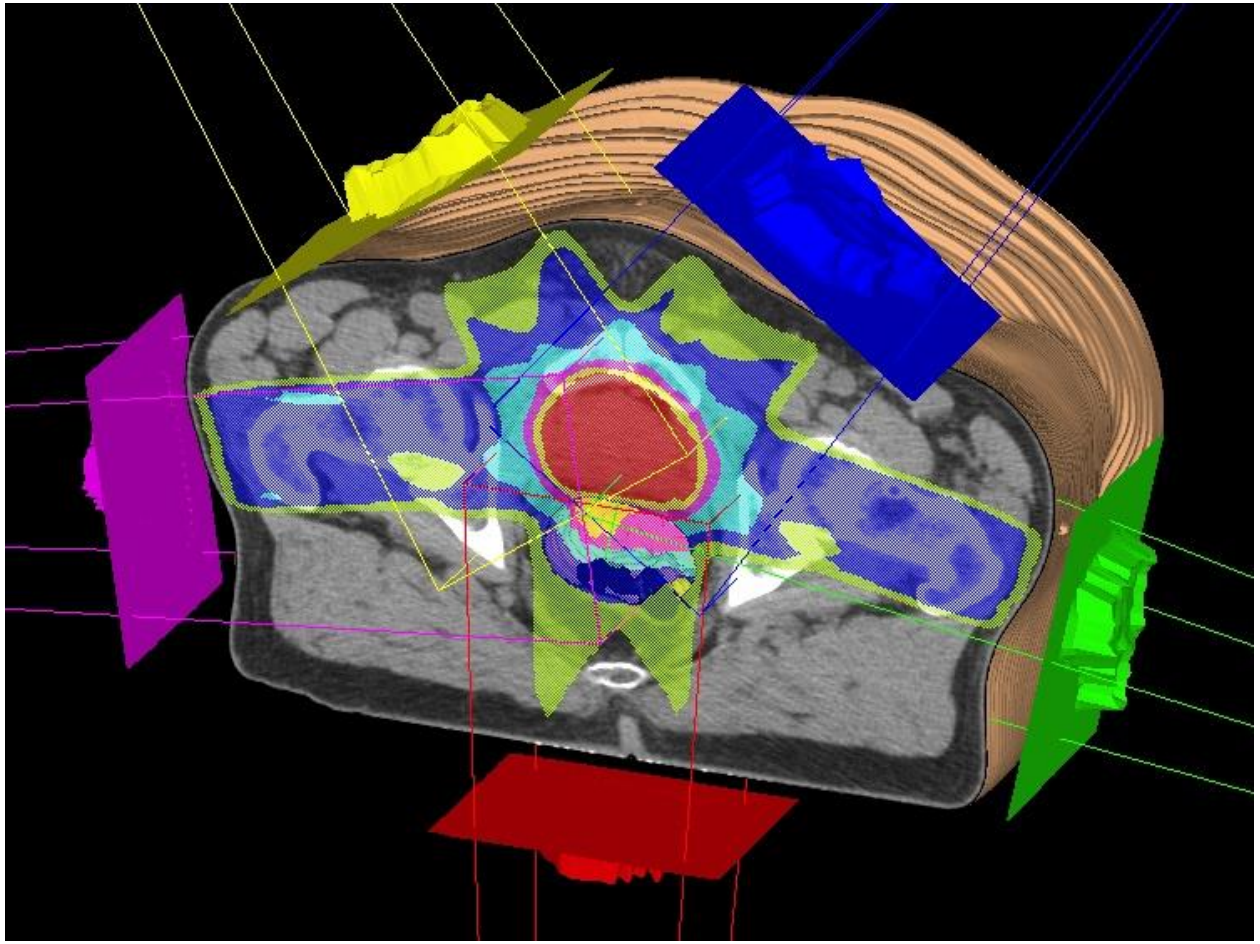
- Understand the basics of IMRT planning
- Be able to describe different methods of IMRT delivery

Intensity Modulated Radiation Therapy

Definition: IMRT is the delivery of radiation to the patient via fields that have non-uniform radiation fluence.

S. Webb, Royal Marsden NHS, London, 2003

Intensity Modulated Radiation Therapy



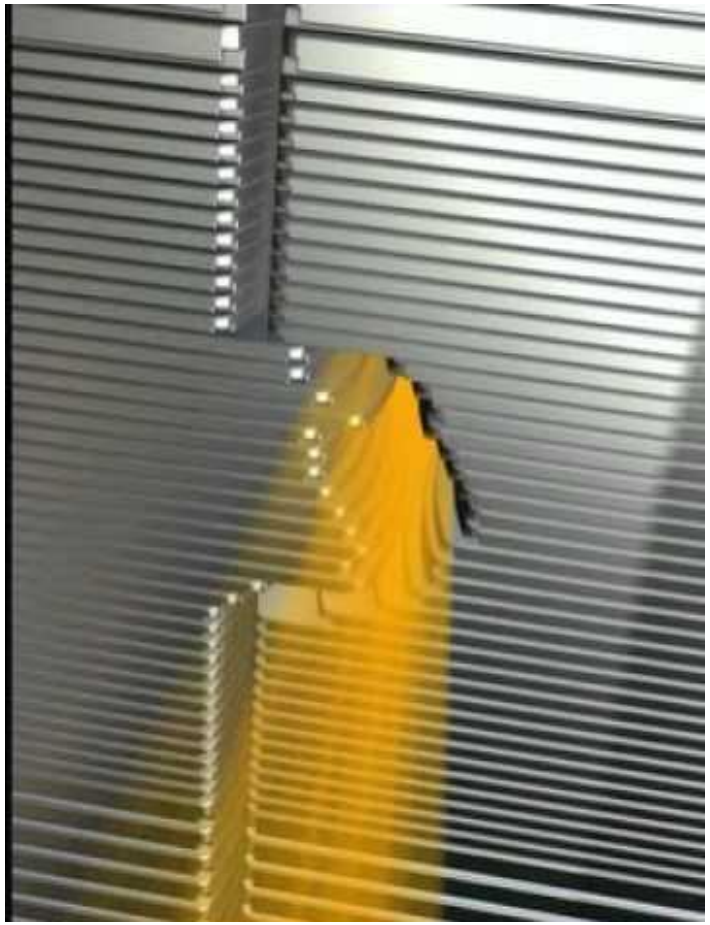


Image courtesy of Varian Medical Systems

Clinical Benefits

- Prescribed dose conforms to target
- Ability to treat concave or ring shaped targets
- Conformal avoidance of OARS
- Simultaneous integrated boost

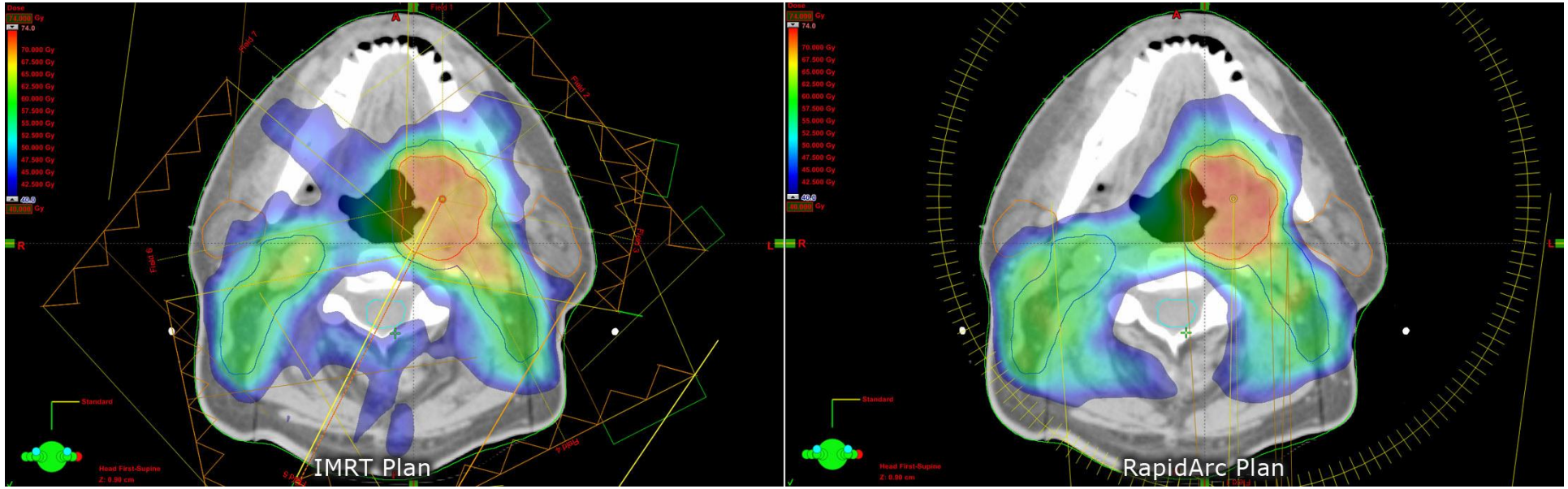
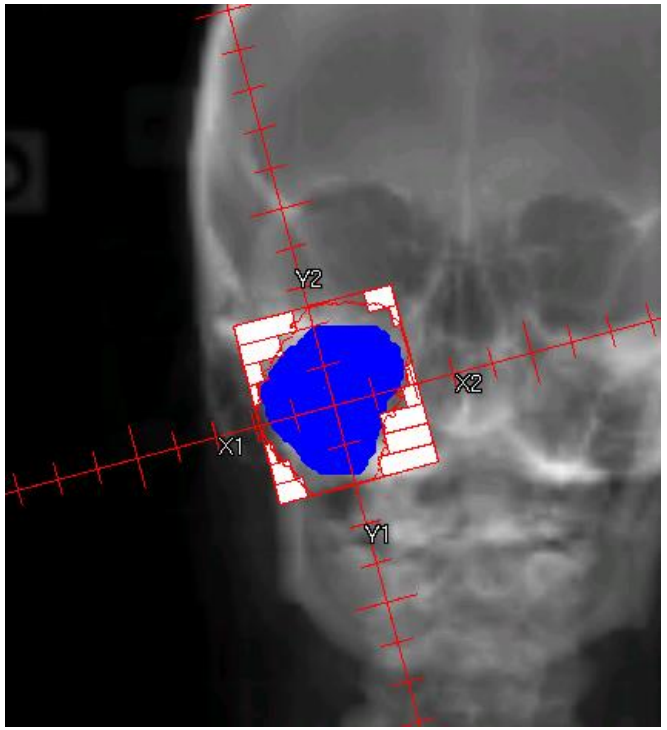
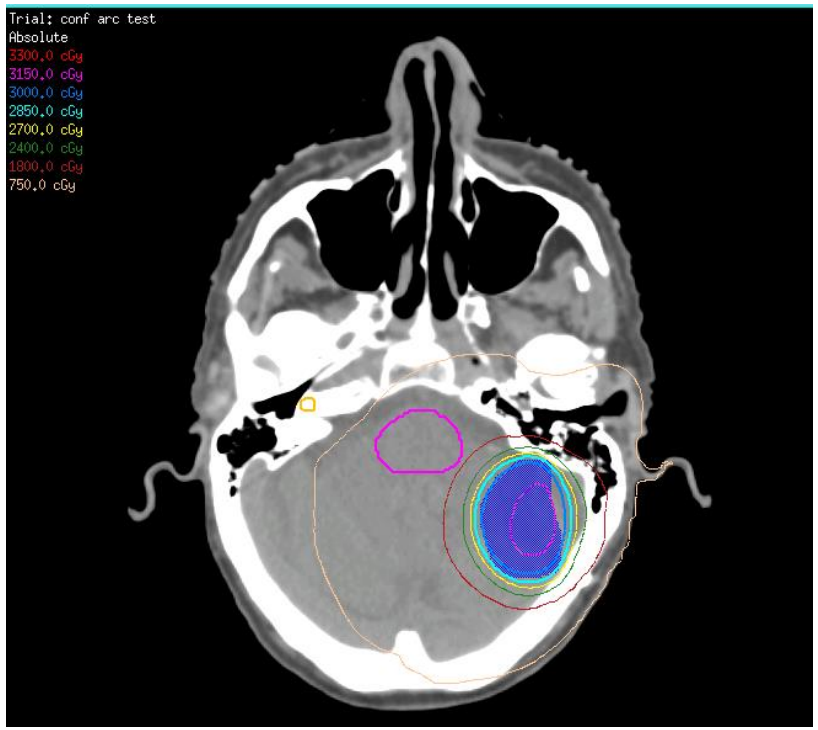


Image courtesy of Varian Medical Systems

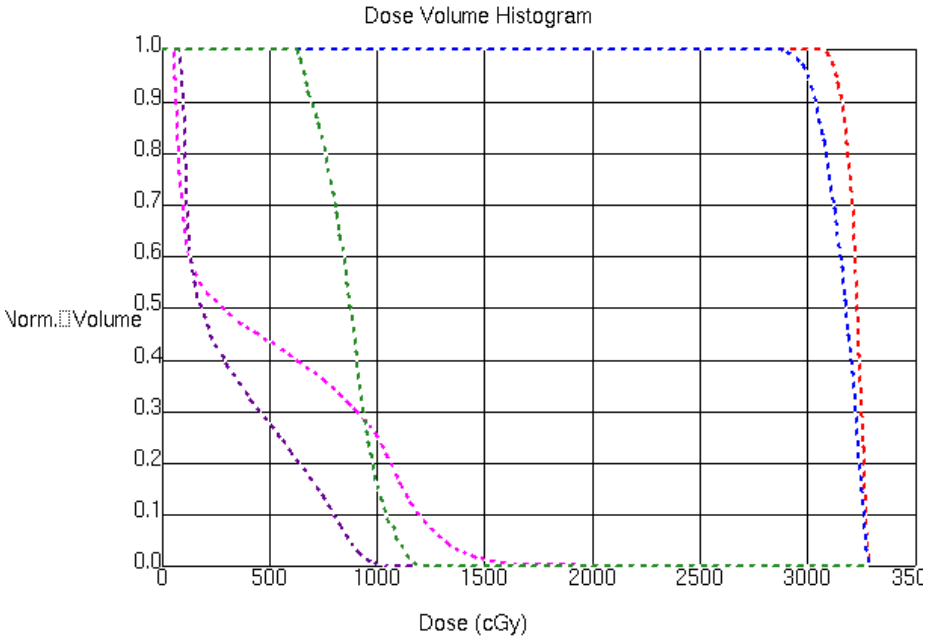
Forward Planning Review



Planner determines beam apertures



Dose Calculation

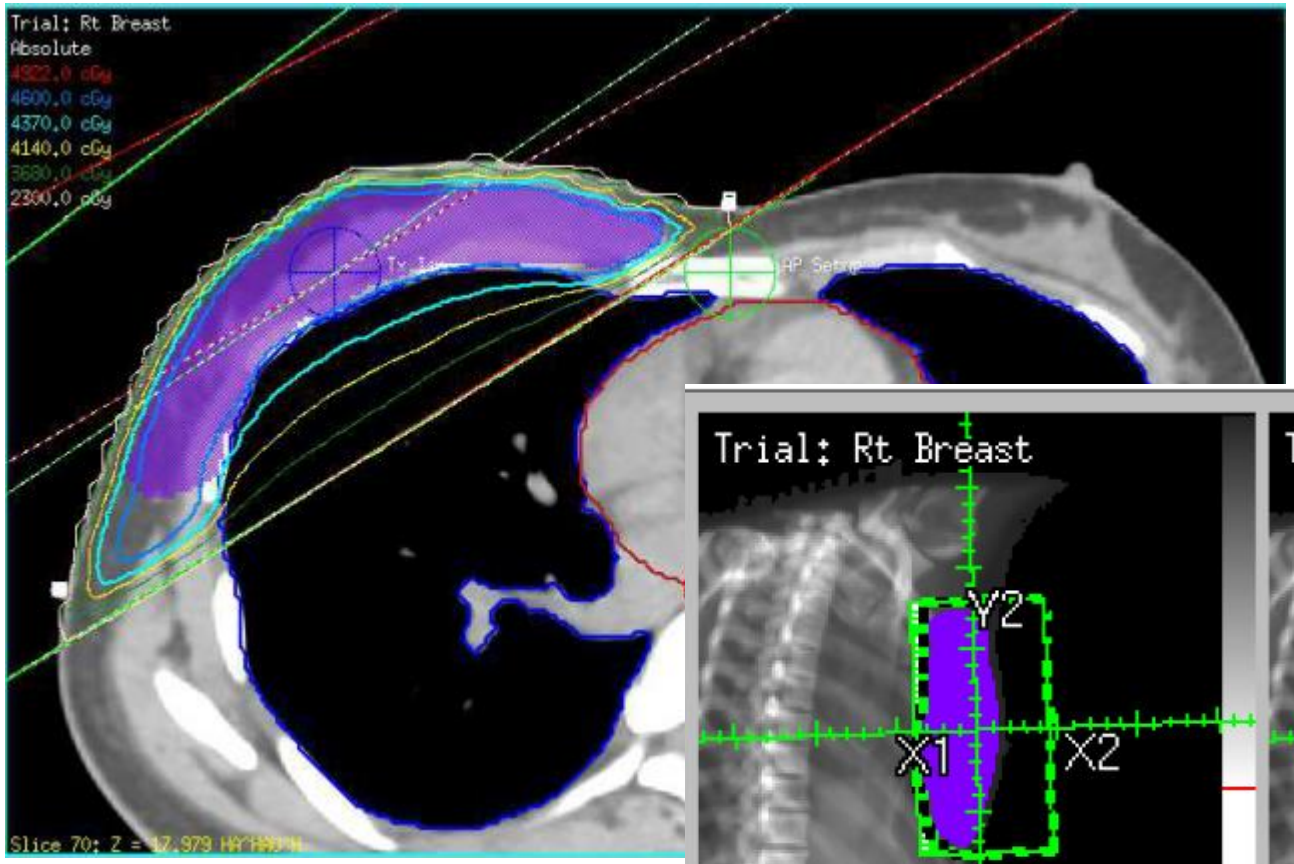


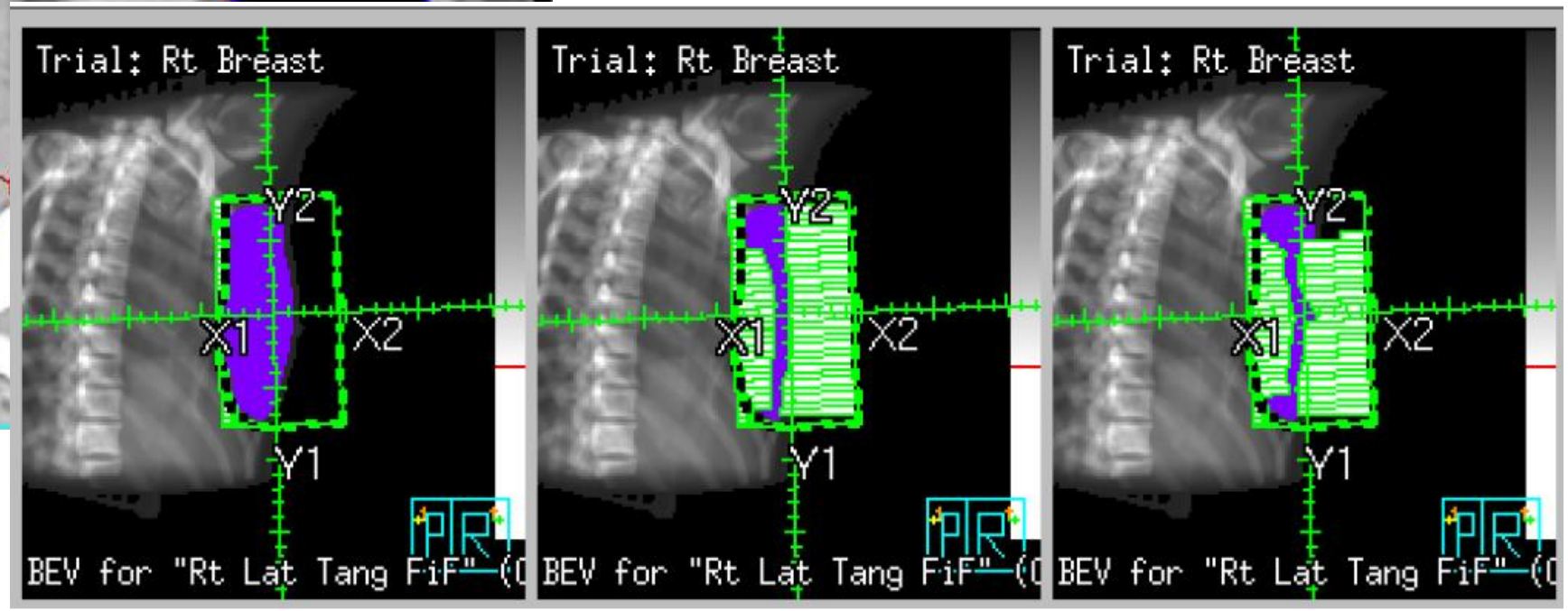
ROI Statistics

Line Type	ROI	Trial or Record	Min.	Max.	Mean	Std. Dev.
◇	Cavity	conf arc test	3044.8	3287.9	3220.6	43.6
◇	PTV	conf arc test	2631.6	3287.9	3159.9	86.5
◇	BrainStem	conf arc test	48.4	1920.6	516.4	473.9
◇	SpinalCord	conf arc test	84.5	1027.2	331.7	274.6
◆	Cochlea_L	conf arc test	629.7	1175.8	872.2	126.1

DVH constructed from dose grid.

Forward Planned Intensity Modulation





Inverse Planning

Definition: The inverse planning approach can be defined as a method of radiation treatment planning where one starts with the desired dose distribution, or clinical objectives, and then determines the treatment parameters that will achieve it.

UCSF Web Site, IPSA Publication, 2015

History

Phys. Med. Biol., 1982, Vol. 27, No. 10, 1221–1229. Printed in Great Britain

Solution of an integral equation encountered in rotation therapy

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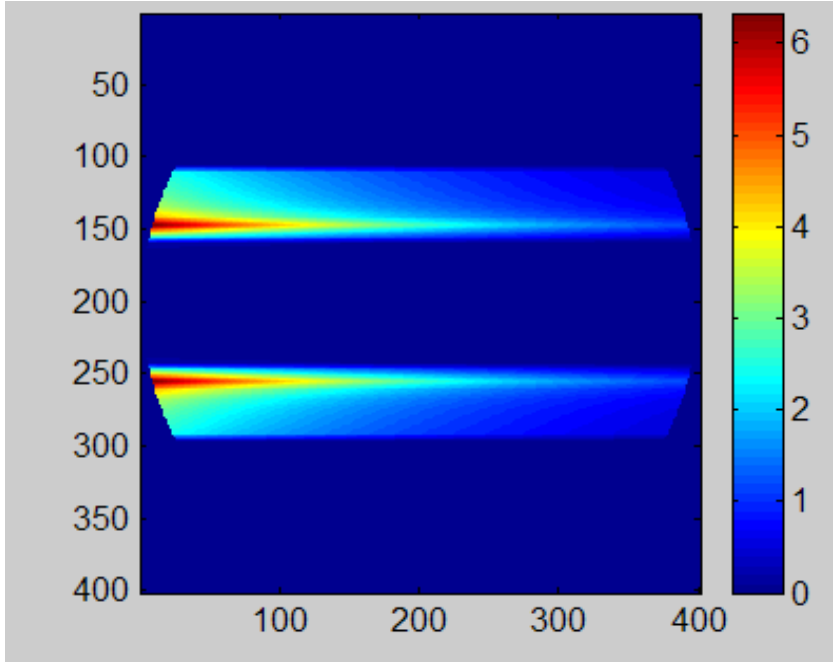
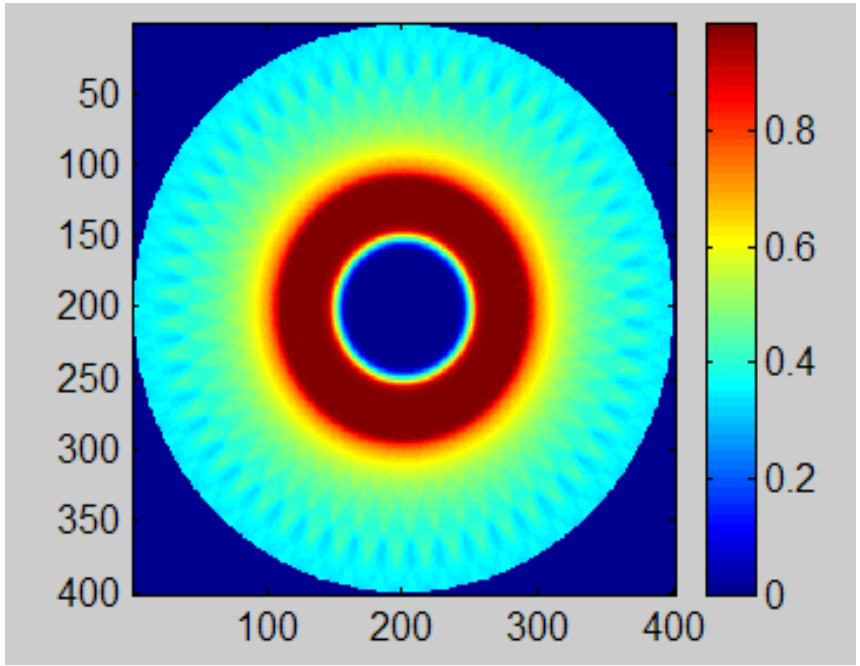
Received 30 March 1981, in final form 4 December 1981

Abstract. An integral equation relating the lateral absorbed dose profile of a photon beam to the resultant absorbed dose distribution during single-turn rotating-beam therapy has been set up and solved for the case of a cylindrical phantom with the axis of rotation coinciding with the axis of symmetry of the cylinder. In the first approximation the results obtained are also valid when the axis of rotation is somewhat off-centred, even in a phantom that deviates from circular symmetry, provided the rotation is performed in both clockwise and counter clockwise directions. The calculated dose profiles indicate that improved dose uniformity can be achieved using a new type of non-linear wedge-shaped filter, which can easily be designed using the derived general analytic solution to the integral equation.





Courtesy of R. Flynn

Radiotherapy and Oncology, 12 (1988) 129–140
Elsevier

RTO 00467

Optimization of stationary and moving beam radiation therapy techniques*

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(Received 30 April 1987, revision received 16 August 1987, accepted 22 January 1988)

Key words: Conformation therapy; Computed dose planning; Treatment optimization

Summary

A new approach is suggested for the optimization of stationary and more general moving beam type of irradiations. The method reverses the order of conventional treatment planning as it derives the optimum incident beam dose distributions from the desired dose distribution in the target volume. It is therefore deterministic and largely avoids the trial and error approach often applied in treatment planning of today. Based on the approximate spatial invariance of the convergent beam point irradiation dose distribution, the desired dose distribution in the target volume is analyzed in terms of the optimum density of such point irradiations. Since each point irradiation distribution is optimal for the irradiation of a given point and due to the linearity of individual energy depositions or absorbed dose contributions, the resultant point irradiation density will also generate the best possible irradiation of an extended target volume when the maximum absorbed dose at a certain distance from the target should be minimized. The optimum shape of the incident beam for each position of the gantry is obtained simply by inverse back projection of the point irradiation density on the position of the radiation source for that orientation of the incident beam.

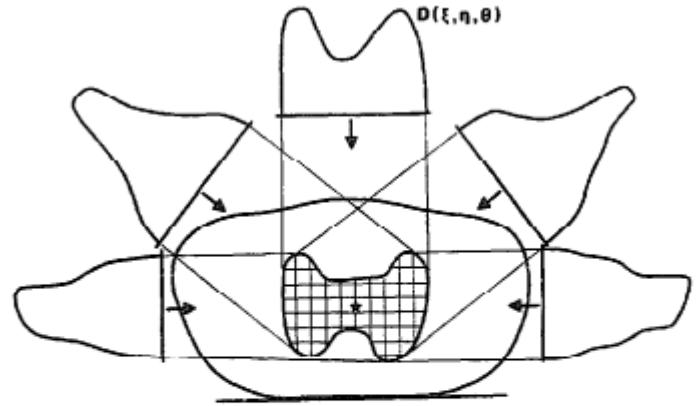


Fig. 4. Schematic illustration of the type of dose delivery that will give the desired dose distribution in the target volume (shaded) and at the same time minimal dose to surrounding normal tissues. The angular dependent dose distributions are most effectively generated using scanned photon beams [5,14,15,18]. For simplicity, the corresponding dose distributions from below are left out in the figure. The location of isocenter (star) is rather uncritical for the present irradiation technique.

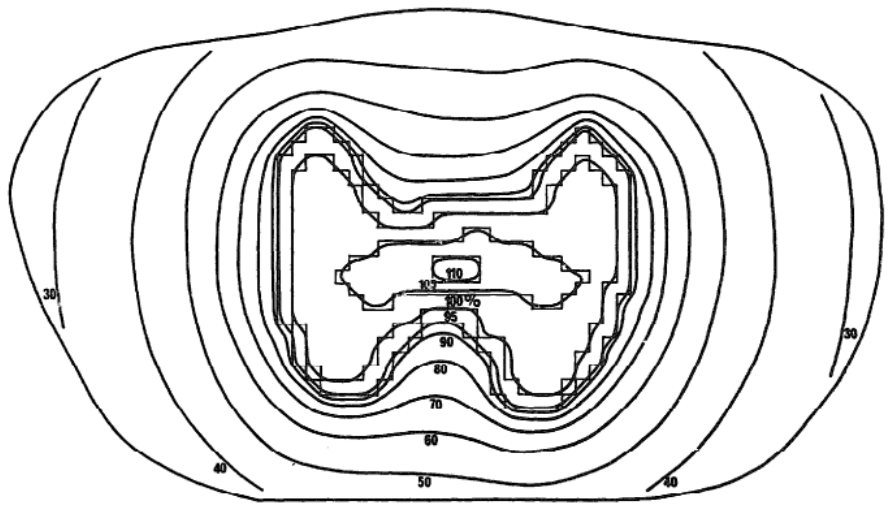


Fig. 5. The resultant dose distribution in the patient when using the target volume of Figs. 3 and 4 and the incident beams according to Fig. 4. It is seen that the isodoses very accurately follow the shape of the target volume which is defined by the 95% isodose.

IMRT Planning Process

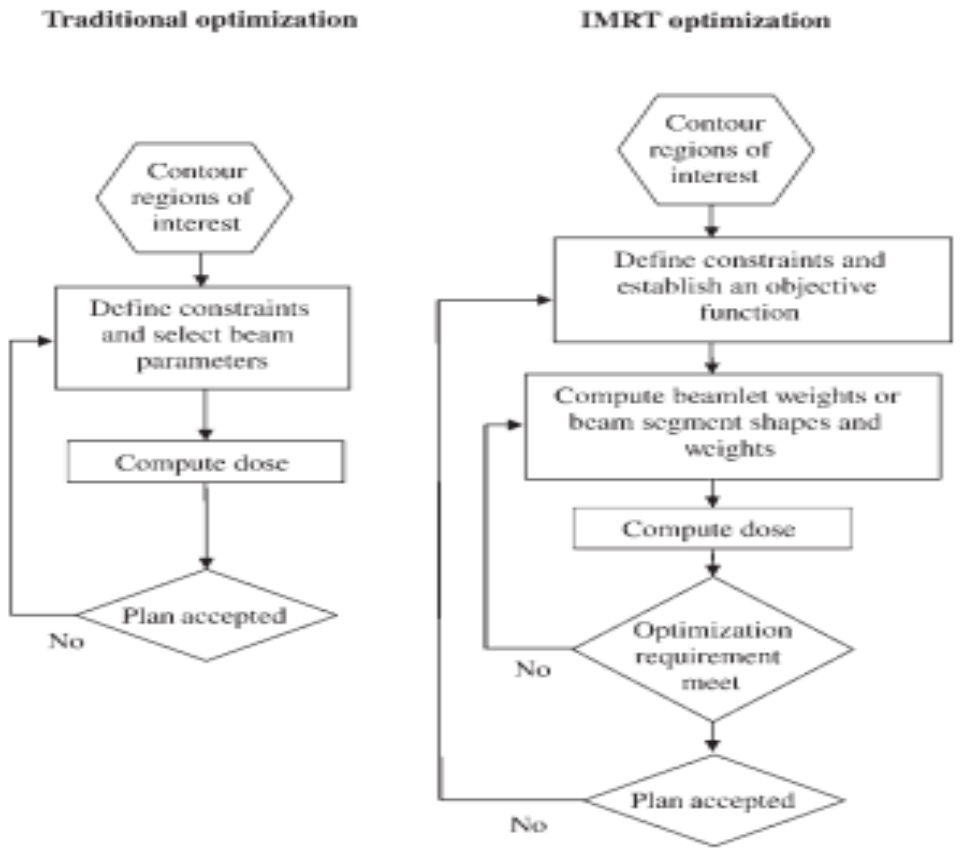


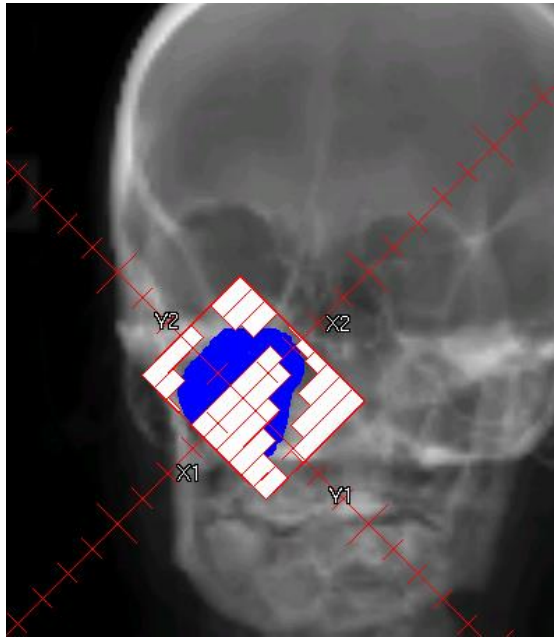
Figure 2.1. Comparison between traditional (left) and IMRT (right) optimization processes.

From Journal of the ICRU, Report 83 c

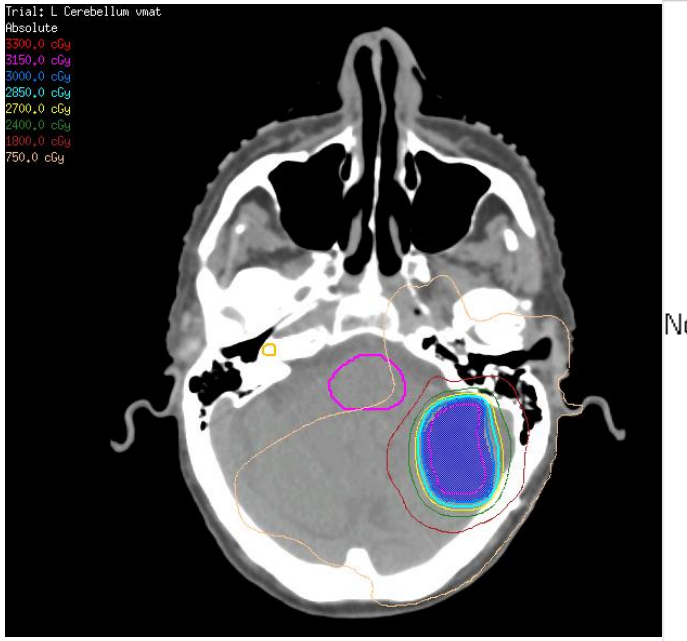
Inverse Planning

BrainStem	Max DVH		800	3	5
Cochlea_L	Max DVH		700	5	5
PTV	Uniform Dose		3000		1

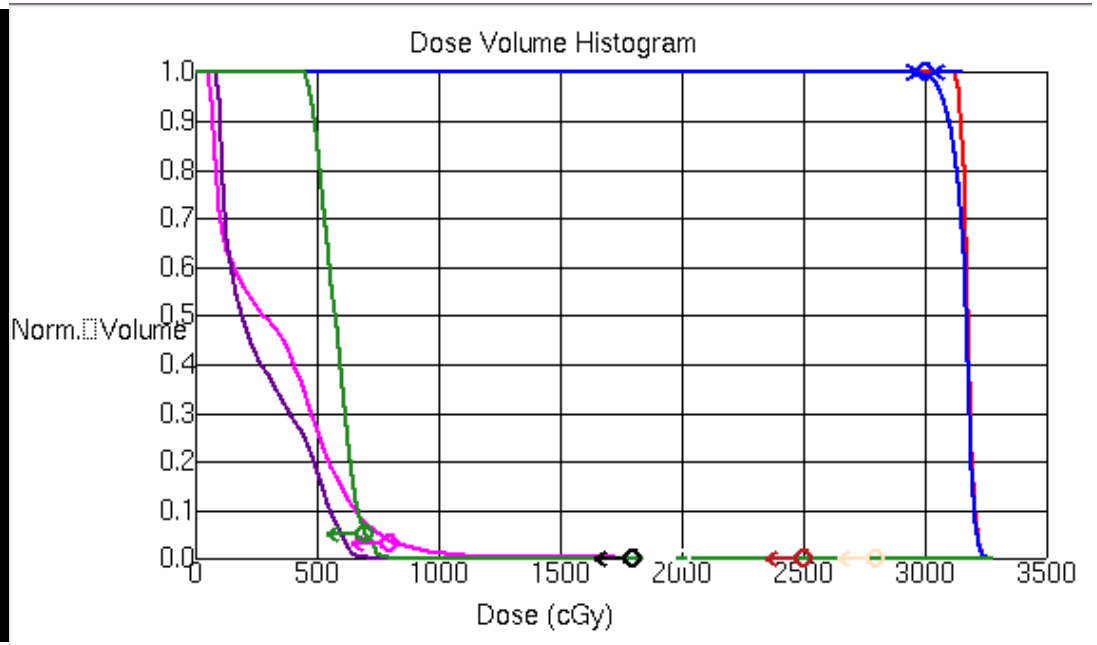
Planner enters objective and constraints and some beam parameters



TPS determines fluence and leaf sequencing



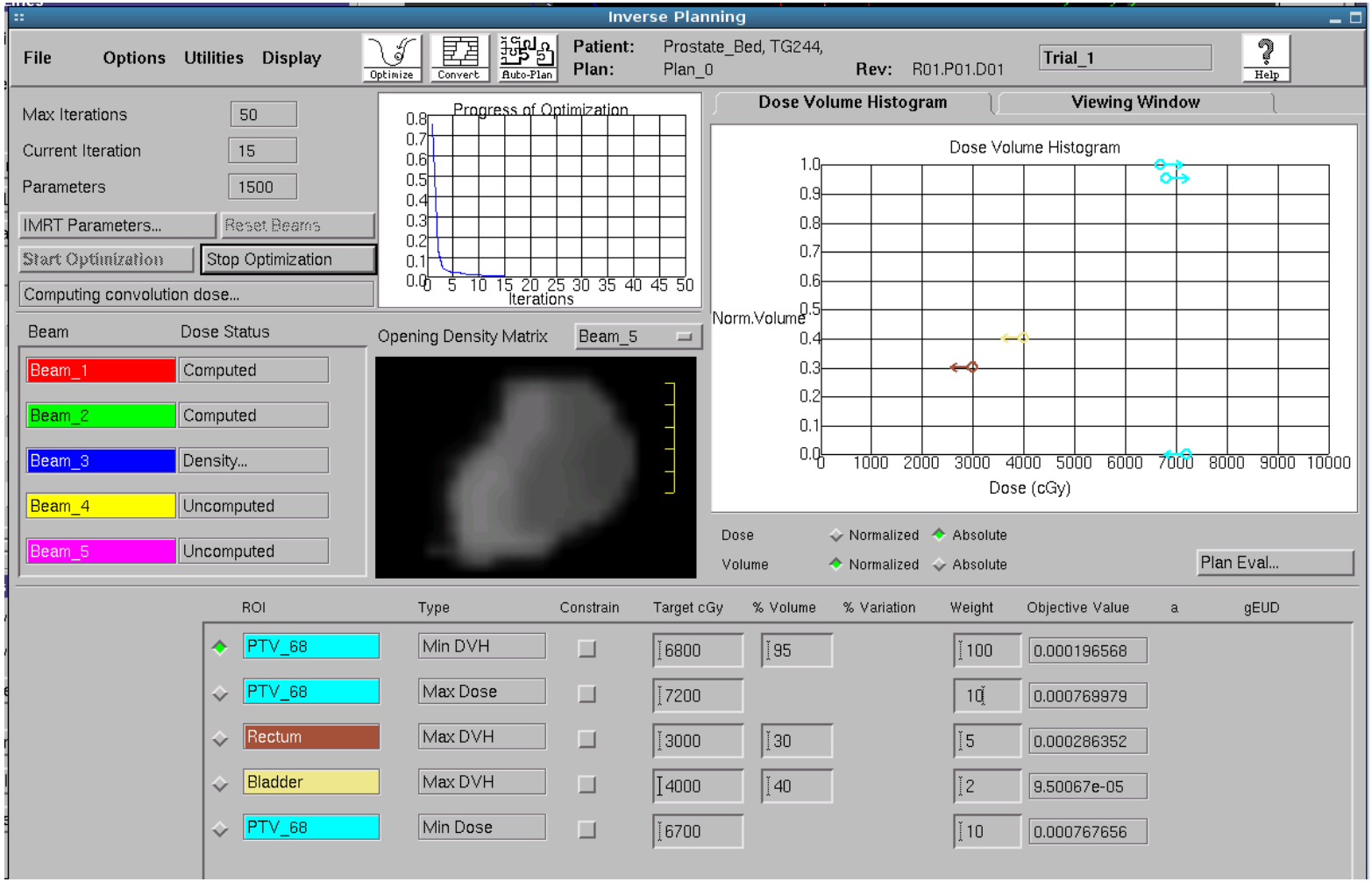
Dose Calculation



Comparison between achieved distribution and requested until user stops the process.

Optimization Process

- Define structures
- Enter constraints
- Determine Weights
- Optimize Fluence
- Leaf sequencing
- Full Scatter Calculation
- Evaluate



Constraints and Objectives

Constraints and objectives are used to characterize the desired dose distribution.

Definitions:

Dose Constraints – Dose criteria that MUST be achieved. Plans that do not meet these criteria will be rejected and optimizer will make all necessary compromised to meet them.

Dose Objectives – Dose criteria that should be prioritized but an acceptable plan may violate these criteria to meet constraints

Types of Plan Objectives

- Minimum dose, maximum dose, mean dose
- Dose volume constraints
  - Specify how much of the volume can receive XGy or More
  - Specify how much of the volume can receive Y% or less
- Objectives must be clearly stated and prioritized prior to planning

AAPM REPORT NO. 263

Standardizing Nomenclatures in Radiation Oncology

The Report of AAPM Task Group 263

January 2018

THE REPORT OF AAPM TASK GROUP 263:
Standardizing Nomenclatures in Radiation Oncology

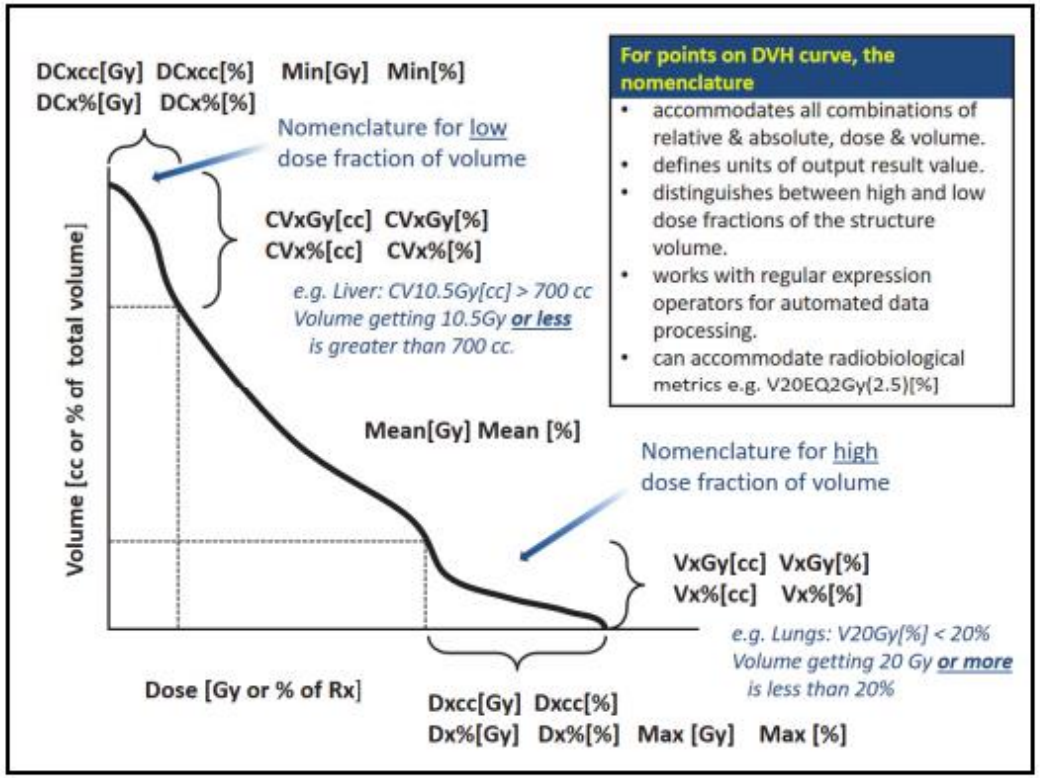


Figure 4. Illustration of standardized DVH nomenclature specifying input and output units. Approach is compatible with use of regular expressions.

Arm 2: Four Fractions (12 x 4 Gy)

Serial Tissue	Volume	Volume Max (Gy)	Max Point Dose (Gy)	Endpoint (≥Grade 3)
Spinal Cord	<0.35 cc <1.2 cc	20.8 Gy (5.2 Gy/fx) 13.6 Gy (3.4 Gy/fx)	26 Gy (6.5 Gy/fx)	myelitis
Esophagus*	<5 cc	18.8 Gy (4.7 Gy/fx)	30 Gy (7.5 Gy/fx)	stenosis/fistula
Brachial Plexus	<3 cc	23.6 Gy (5.9 Gy/fx)	27.2 Gy (6.8 Gy/fx)	neuropathy
Heart/Pericardium	<15 cc	28 Gy (7 Gy/fx)	34 Gy (8.5 Gy/fx)	pericarditis
Great vessels	<10 cc	43 Gy (10.75 Gy/fx)	49 Gy (12.25 Gy/fx)	aneurysm
Trachea and Large Bronchus*	<4 cc	15.6 Gy (3.9 Gy/fx)	34.8 Gy (8.7 Gy/fx)	stenosis/fistula
Rib**	<1 cc	32 Gy (8 Gy/fx)	40 Gy (10 Gy/fx)	Pain or fracture
Skin	<10 cc	33.2 Gy (8.3 Gy/fx)	36 Gy (9 Gy/fx)	ulceration
Stomach	<10 cc	17.6 Gy (4.4 Gy/fx)	27.2 Gy (6.8 Gy/fx)	ulceration/fistula
Parallel Tissue	**Critical Volume (cc)**	**Critical Volume Dose Max (Gy)**		**Endpoint (≥Grade 3)**
Lung (Right & Left)	1500 cc	11.6 Gy (2.9 Gy/fx)		Basic Lung Function
Lung (Right & Left)	1000 cc	12.4 Gy (3.1 Gy/fx)		Pneumonitis

***Avoid circumferential irradiation**

Inverse Optimization

Optimization – Process of changing beam parameters to search for the closest solution to the desired dose distribution

Iteration – Each cycle where beam parameters are changed, dose is calculated, cost is calculated

Plan Evaluation - Cost Function

- Plan objectives are mathematically formulated as a quadratic objective (cost) function to be used to evaluate plan solutions
- Beamlet weights for a given number of beams are iteratively adjusted to minimize the value of a cost function

Objective Function

- Goal is to minimize the sum of the squared differences between the prescribed and calculated dose
- Two types
  - Target type- a function that aims to increase the dose from zero
  - OAR type- a function that penalizes dose above some level
- Overall cost is the sum of the costs for all targets.
- Ideally all constraints are achieved and C_n approaches zero

$$C_n = \left[\left(\frac{1}{N} \right) \sum_r W(\vec{r}) \left(D_0(\vec{r}) - D_n(\vec{r}) \right)^2 \right]^{0.5}$$

N=number of dose points,
n=iteration number
r=point in patient
D_0=target dose
D_n=dose achieved for iteration n
W=weight

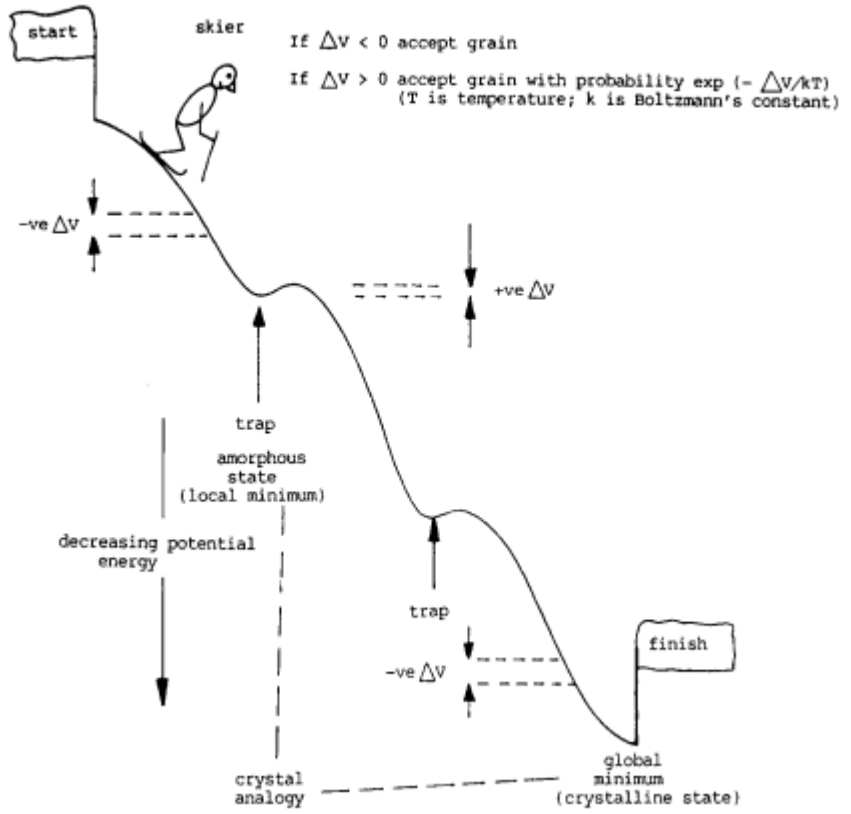
See Khan F and Gibbon J. The Physics of Radiation Therapy, Fifth Edition. Chapter 20.

Fluence Optimization Algorithms

- These algorithms are looking for the best intensity distribution to accomplish the treatment goals from the large number of possible solutions
- Solutions that decrease the cost will be accepted
- Optimization can stop when subsequent changes do not lower the cost
- Optimization is longer and more time consuming as the solution space increases

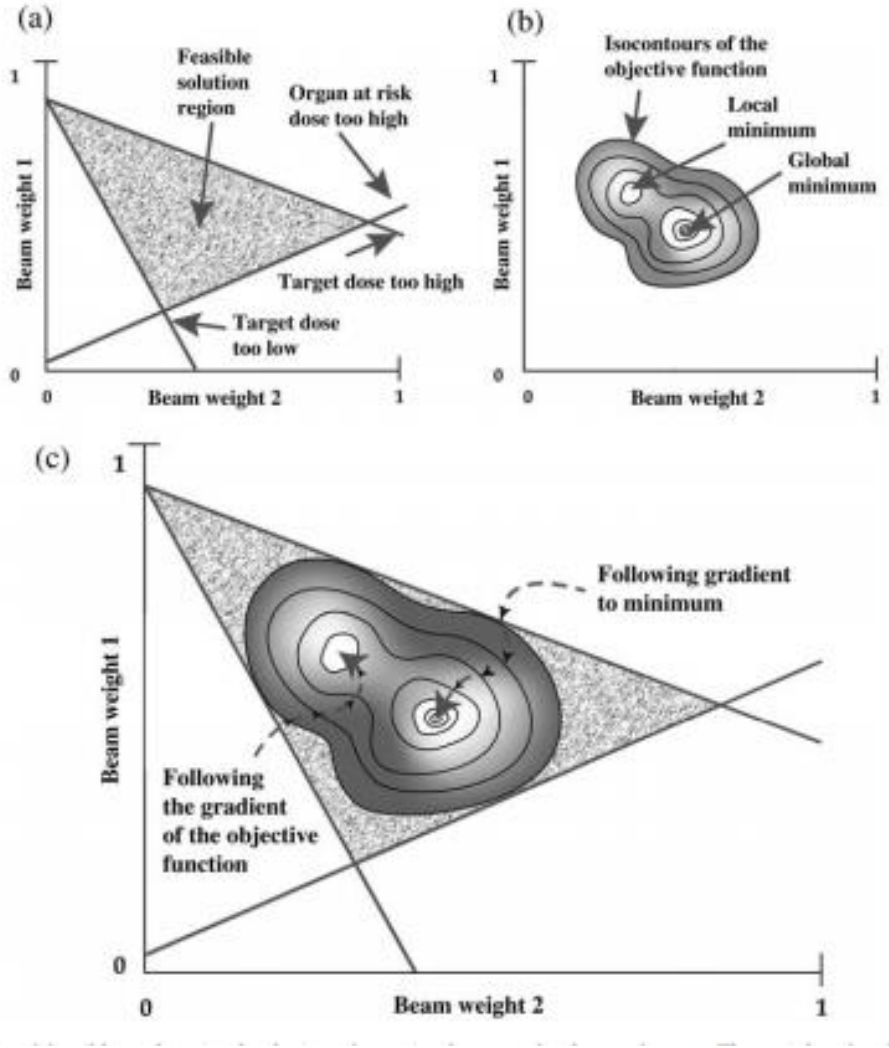
Optimization Algorithms

- Objective function has many parameters
- Complex algorithm needed to search solution space
  - Gradient descent
  - Stochastic annealing
  - Neural networks
  - Genetic algorithms
- Searching for a global minimum but local minimum sometimes found



From S. Webb. The physical basis of IMRT and Inverse Planning. BJR October 2003.

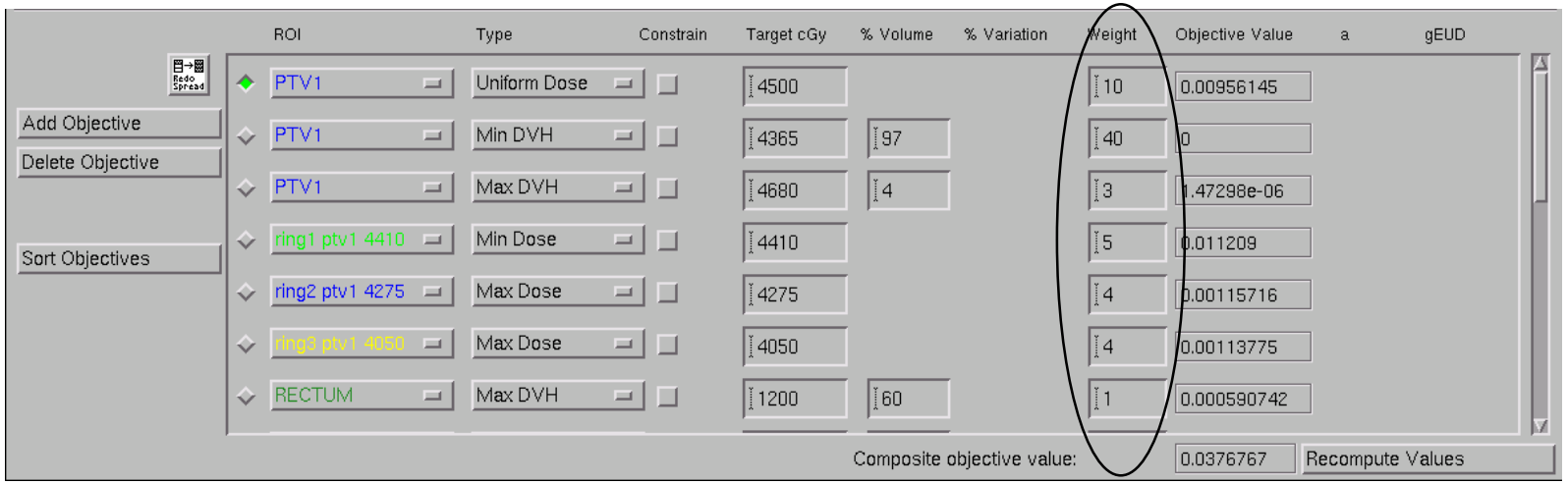
Further Reading on Optimization Theory



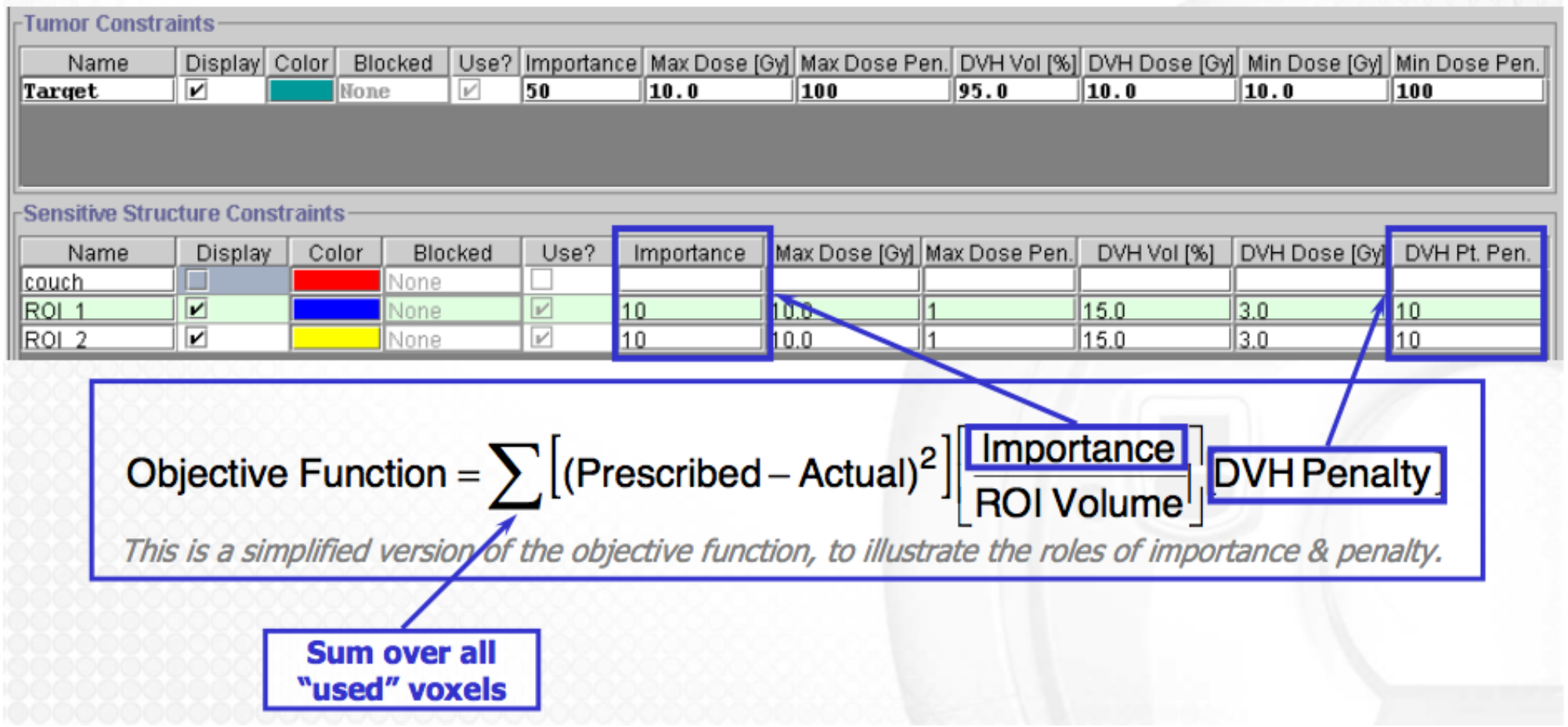
From Journal of the ICRU, Report 83. 2010. Chapter 2. This chapter provides a nice review of optimization strategies in IMRT.

Weights

- Relative weights are given to
  - Structures (normalized to volume)
  - Individual constraints
- PTVs are generally given higher weights



Plan Optimization - TomoTherapy



Slide courtesy of TomoTherapy, Inc. circa 2007

Let's say these are the objectives:
Prostate –V10Gy ≥ 99%
Rectum – V4Gy<35%
Femoral Head – V5Gy<10%
Bladder – V6.5Gy<50%

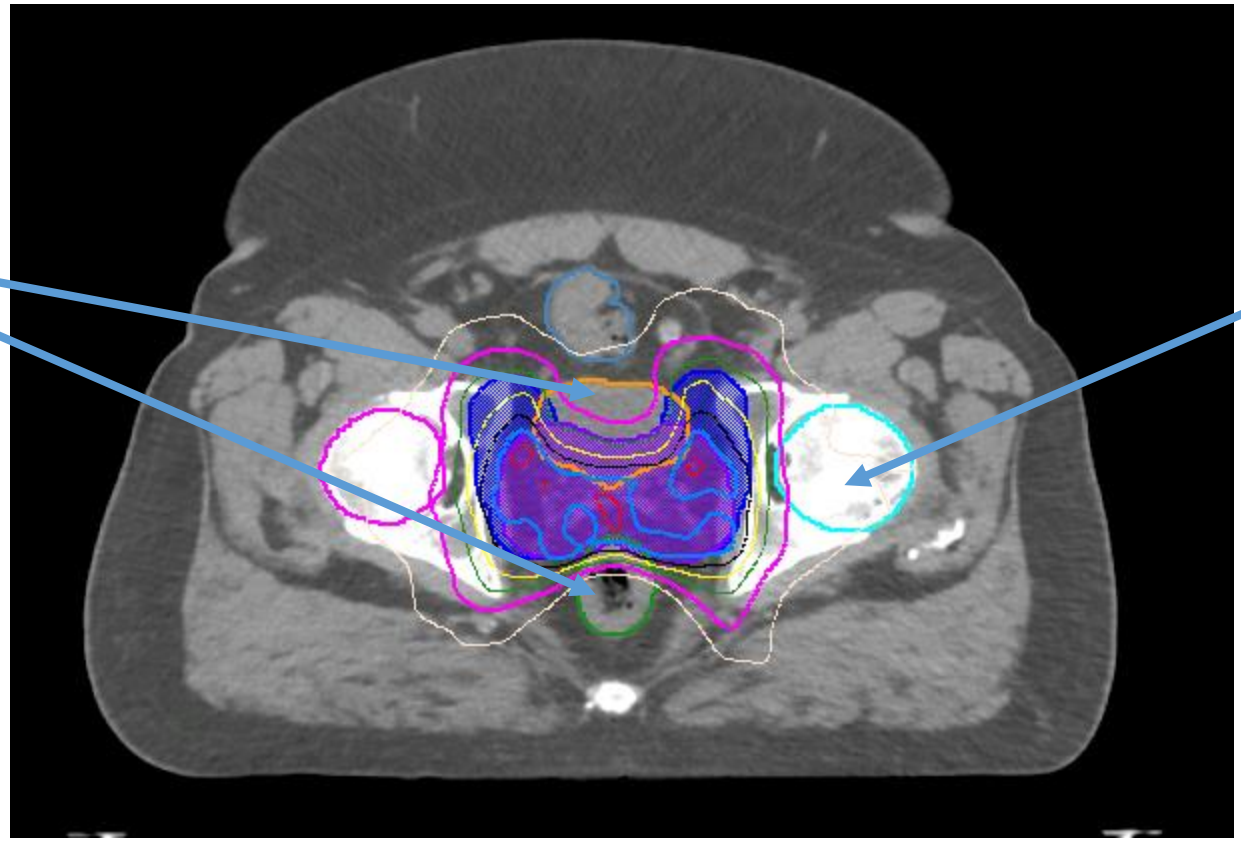
And this is the solution →

10	1.0	3.0	6.5	7.0	7.0	7.5	1.0	1.0	1.0
1.0	2.0	3.0	7.5	8.0	8.5	7.5	5.0	4.0	3.0
1.0	1.0	2.0	3.0	9.5	9.5	9.0	6.0	5.0	5.0
3.0	4.0	5.0	9.5	10	10	9.5	6.0	3.0	2.0
3.0	4.0	5.0	10	10.5	10	10	6.0	3.5	3.0
3.0	4.0	5.0	10	10	10	10	6.0	3.0	2.5
2.0	3.0	4.0	5.0	9.5	9.5	6.0	5.0	4.0	3.0
2.0	3.0	4.0	5.0	9.0	9.0	5.5	4.5	3.5	2.2
2.5	3.5	4.5	6.0	7.0	7.0	6.0	4.5	5.5	6.5
1.0	2.0	3.0	4.0	5.0	5.0	4.0	3.0	2.0	1.0

In the next iteration, beamlet weights/fuence will be changed such that less fluence is entering through the bladder and rectum, possibly more in unassigned normal tissue or fermoral head (that is well below tolerance), and then dose will be calculated again to show the mathematical result is closer to zero.

Final Distribution

Avoids bladder and rectum



More low dose laterally

Leaf Sequencing

- Leaf positions determine from ideal fluence
- Once the MLC is considered the calculated dose will consider
  - Leaf transmission
  - Leaf gap
- Dose distribution recalculated
- Can be difference between calculated dose and optimized fluence

Inverse Planned IMRT Delivery Techniques

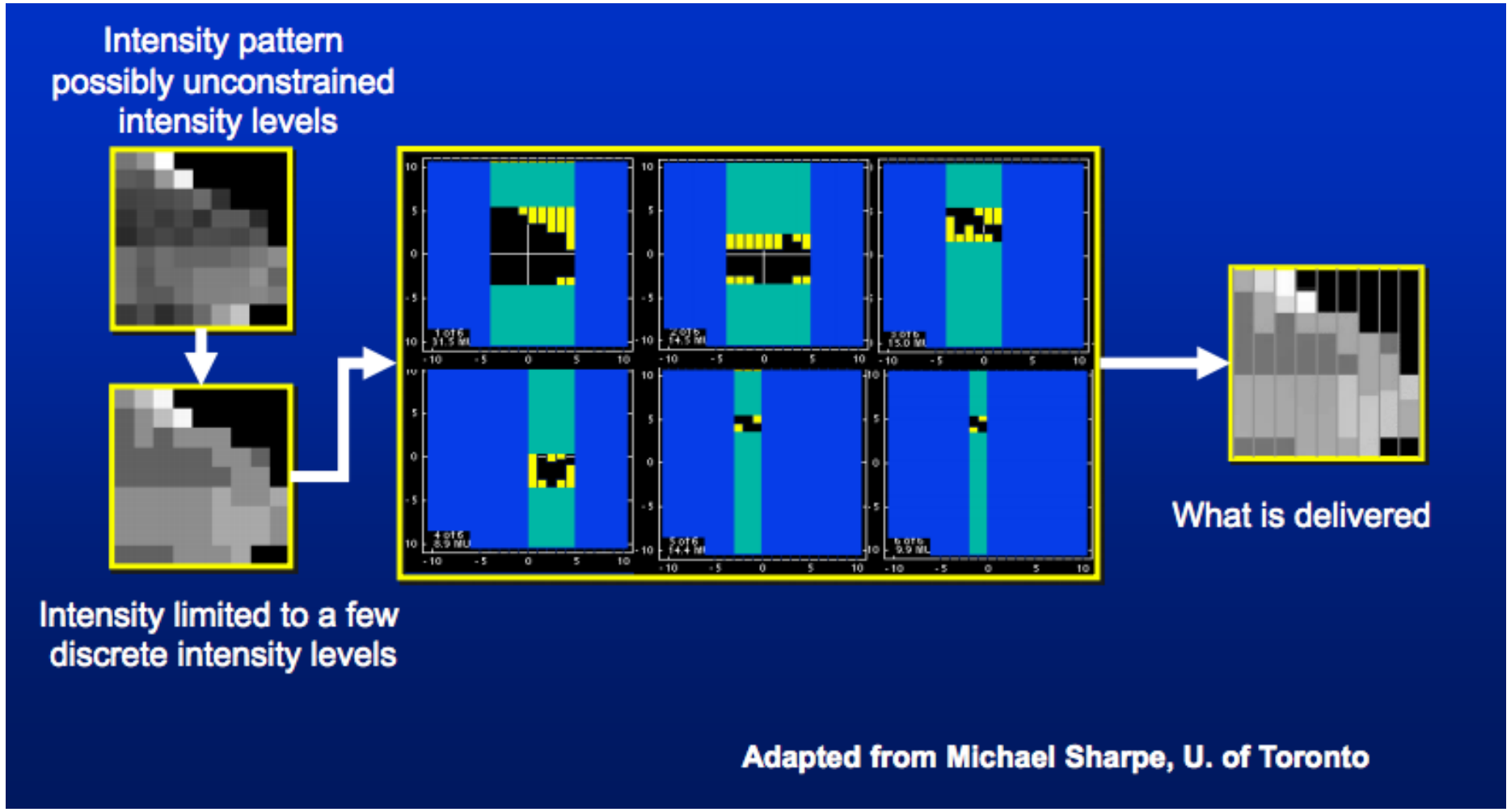
- Static Field – Segmental Delivery (Step and Shoot)
- Static Field – Dynamic Delivery (Sliding Window)
- Rotational – VMAT (SmartArc/Rapidarc/HyperArc)
- Static Field – CyberKnife (many non-coplanar fields, circular collimators)
- Rotational –Tomotherapy (helical slices)

Static field techniques typically use 7-9 non-opposed fields

Static Field: Segmental (Step and Shoot)

- Flunce is delivered through mutliple static segments
- General sequencing algorithm
  - Clusters intensity levels
  - Creates segments from clusters
  - Determine control points based on mechanical limitations
- Treatment times can be long

Step and Shoot IMRT Leaf Sequencing



Slide by Rock Mackie, available on aapm.org

Dynamic Leaf Sequencing

- Dose is modulated by the gap width and speed as MLCs sweep across the field.

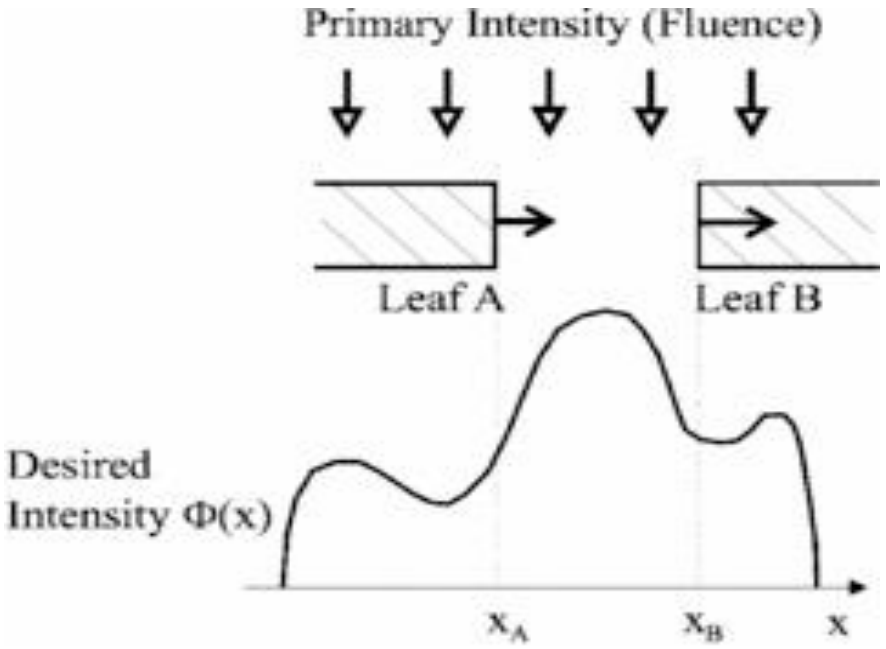


Figure 5 from IMRT: a review and preview
Thomas Bortfeld 2006 Phys. Med. Biol. 51 R363 doi:10.1088/0031-9155/51/13/R21

Machine Parameter Optimization

- Fluence optimization alone can make it difficult to find the best DELIVERABLE solution
- MPO considers physical limitations of the machine in the optimization process
  - Leaf speed/leaf width (static)
  - Dose rate/gantry speed (rotational)
- Total delivery time and dose rate can be also optimized
  - Dose rate could be optimized to fixed or discrete levels if required by the machine

Example Machine Constraints

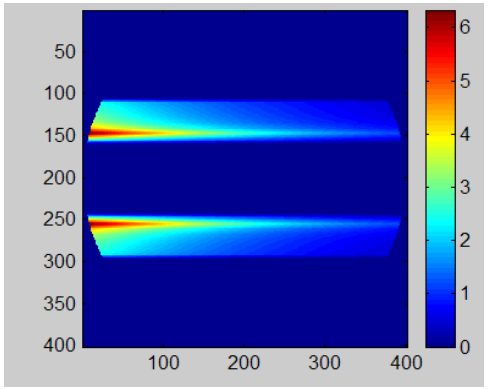
Machine parameter	Constraint
Maximum gantry rate	6 deg/s
Minimum gantry rate	1 deg/s
Maximum MLC leaf speed	2.5 cm/s
Maximum dose rate	600 MU/min
Minimum dose rate varies per case	50–200 MU/min
Maximum leaf travel per degree	0.5 cm/deg

Table 3: Dynamic arc specific linear accelerator specifications used as optimization constraints.

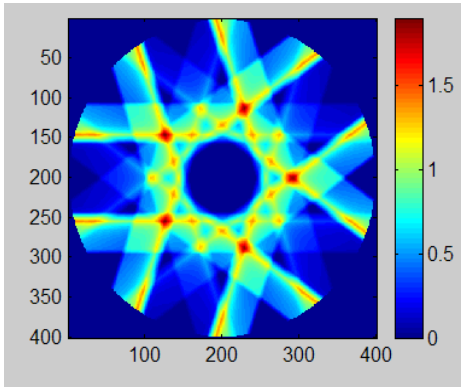
From Pinnacle[3] SmartArc White Paper

Rotational IMRT

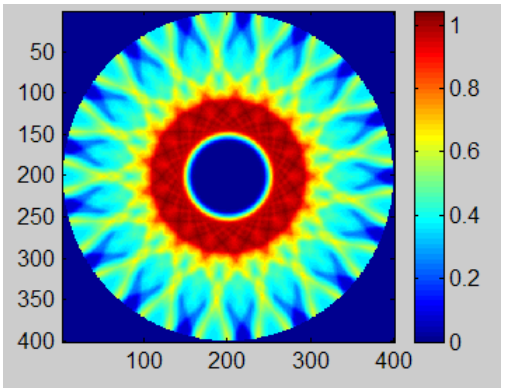
1 Projection



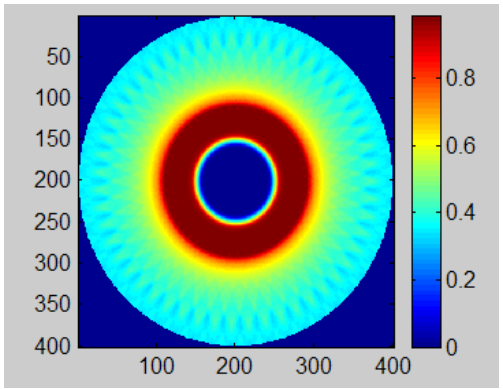
5 Projections

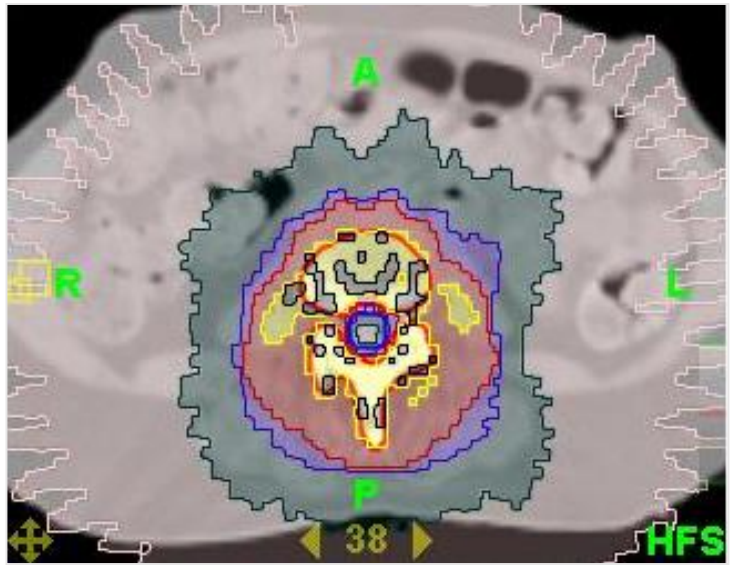


17 Projections



51 Projections



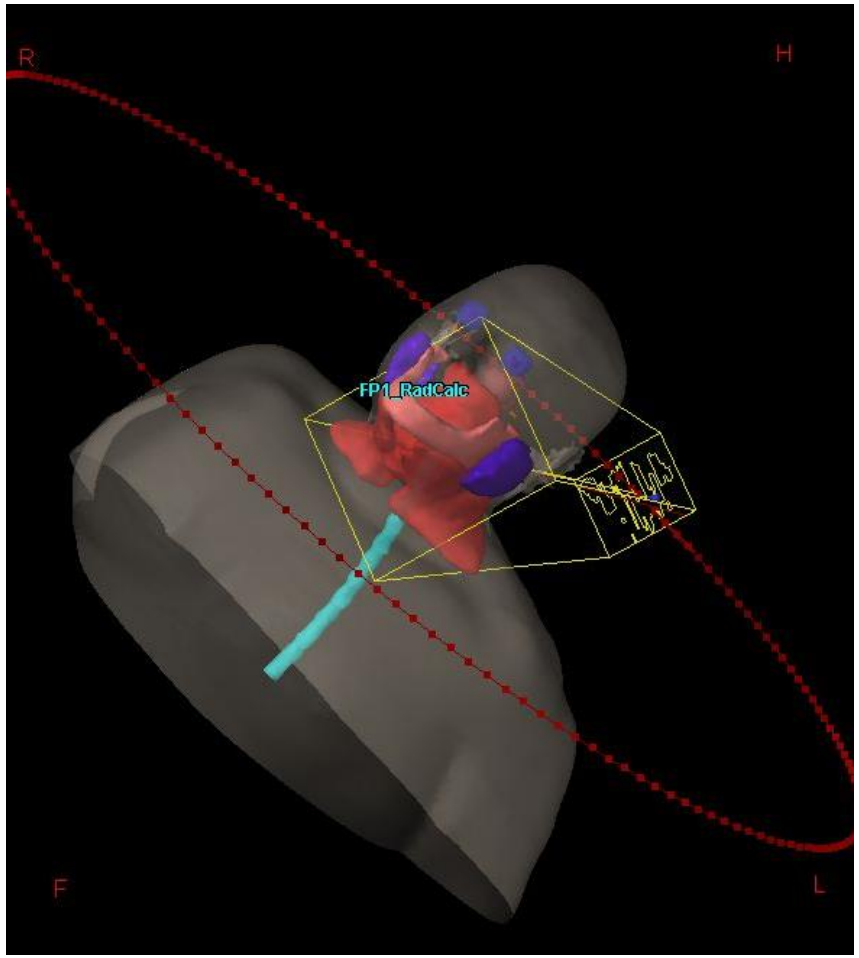


Courtesy of R. Flynn

Volumetric Modulated Arc Therapy (VMAT)

The following parameters change when the beam is on:

- **Gantry Angle**
- **Gantry Speed**
- **MLC shape**
- **Dose Rate**



Volumetric modulated arc therapy: IMRT in a single gantry arc

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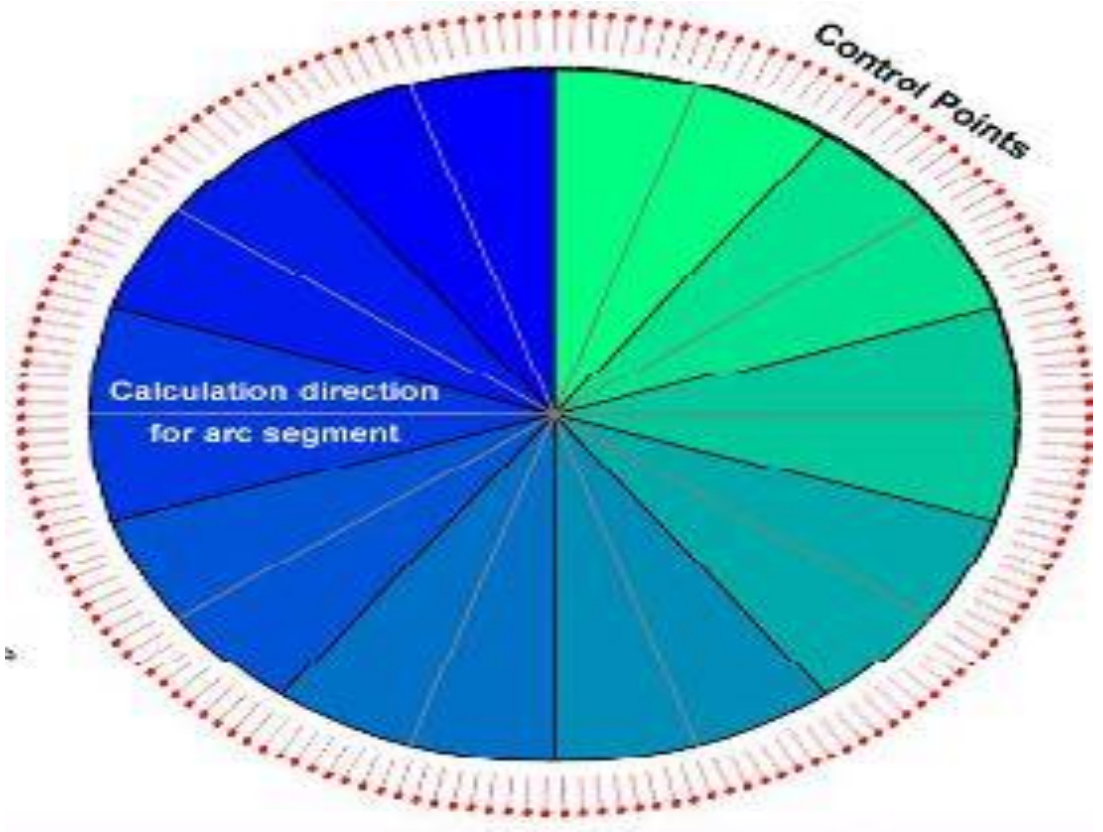
(Received 25 June 2007; revised 21 September 2007; accepted for publication 5 November 2007; published 26 December 2007)

- Developed at BC Cancer Agency (Karl Otto) with work partially funded by Varian
- Goals of the project (from Otto et al.):
  - To create an optimization and delivery platform that is
    - Time efficient
    - Capable of producing highly conformal dose distributions with 360 degree rotations
    - Improved accuracy (high sampling of beam angles)
- Recognized that planning must be fast for plan adaptation

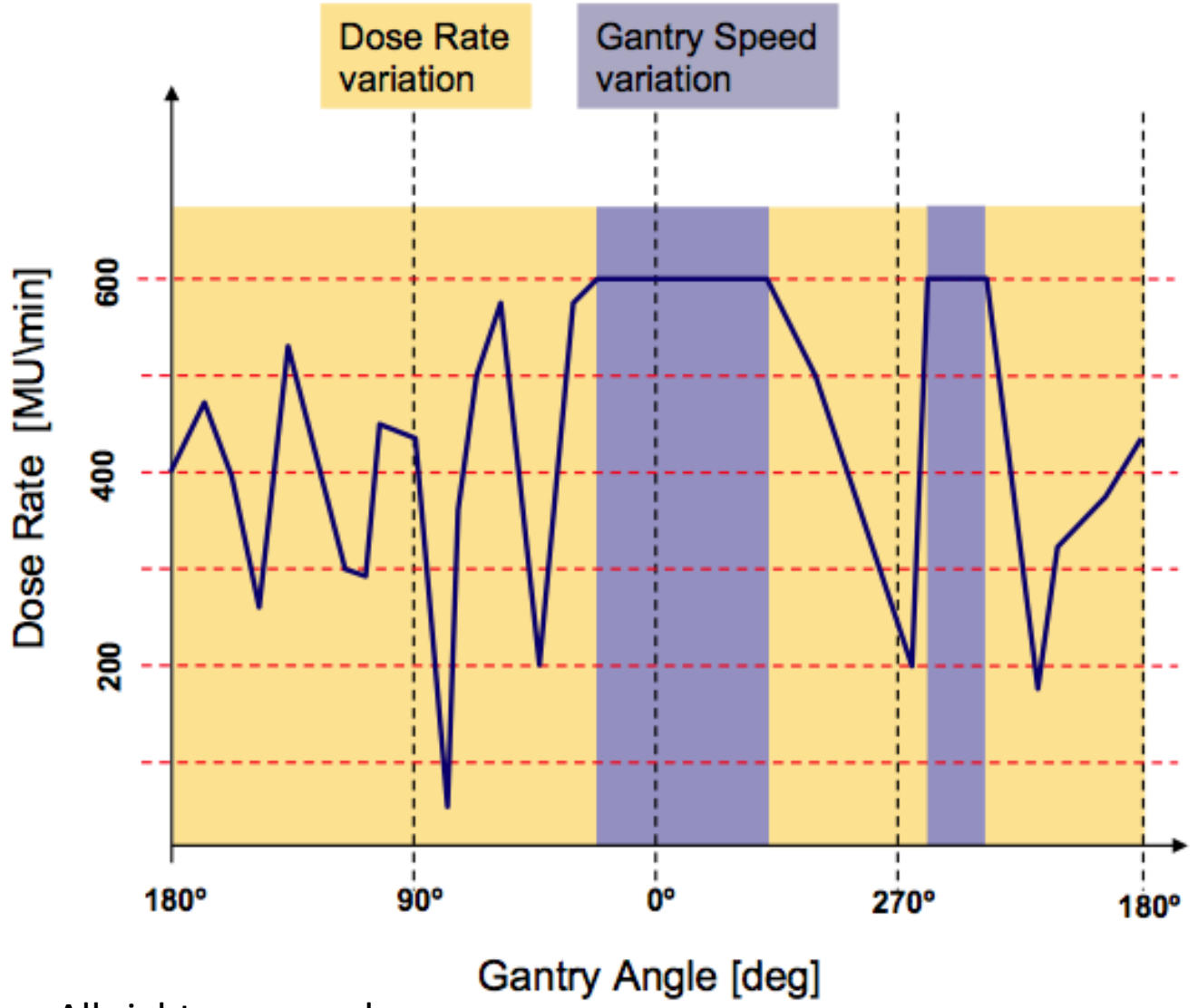
Medical Physics. Vol 35(1). January 2008.

Deliver Mechanics (Varian)

- Each full arc has 178 control points to define the delivery
  - Smaller arcs have less
- To deliver, the delivery system requires:
  - Dose vs. Gantry position
  - Gantry position vs. MLC leaf positions

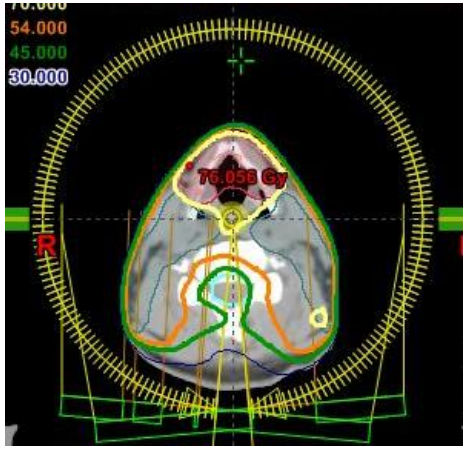


Dose Rate and Gantry Speed

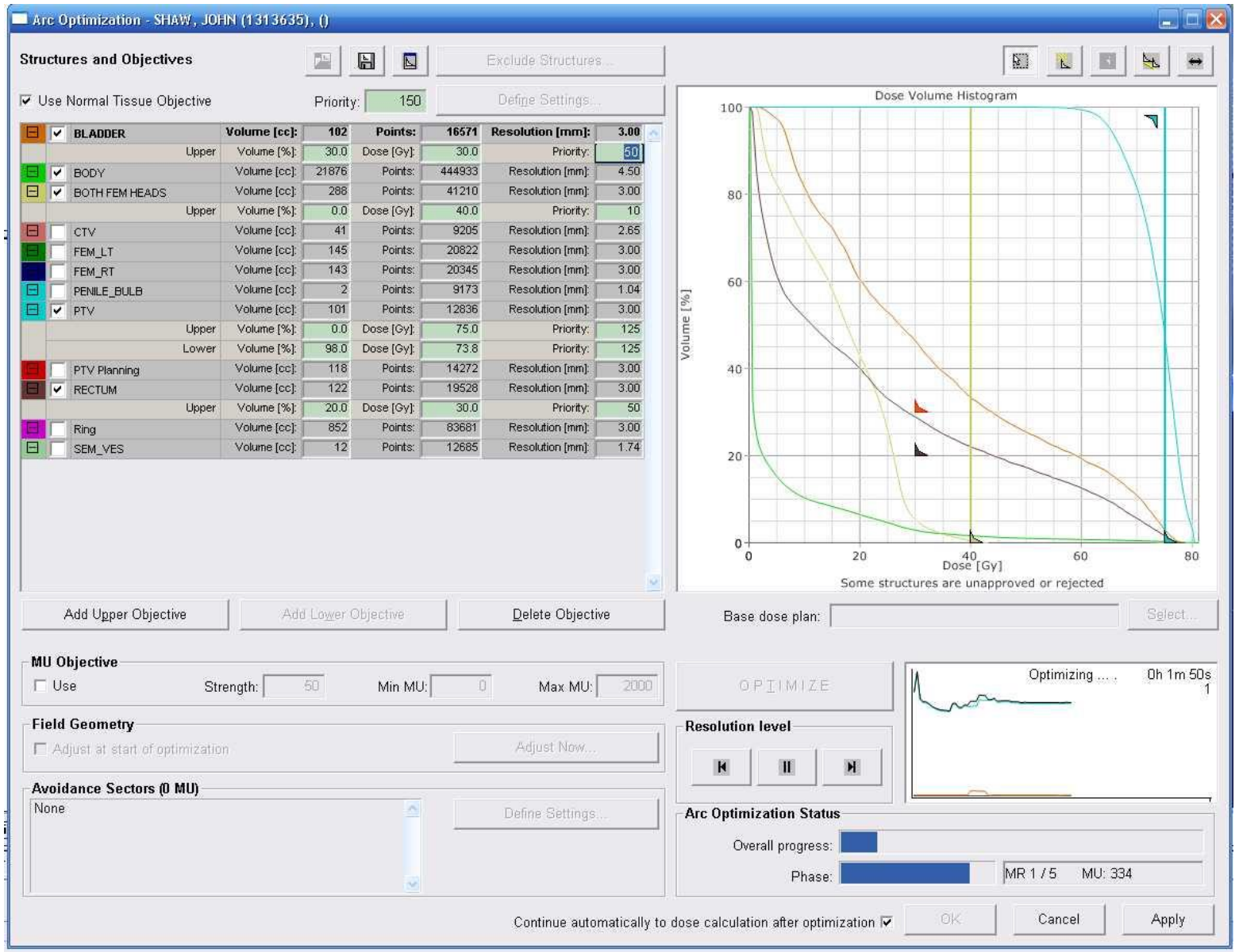


Sample Arc Limitations (Varian)

- 10 Arc Maximum
- Min arc length - 30° degrees
- Avoidance sectors (areas of are where DR = 0 mu/min)
  - 2 per arc, min length 15°
- Collimator cannot be 0° due to leakage between leaves
  - Varian recommends 45°
- Max dose rate specified in planning, (ie. 600 MU/min)



Plan Objectives



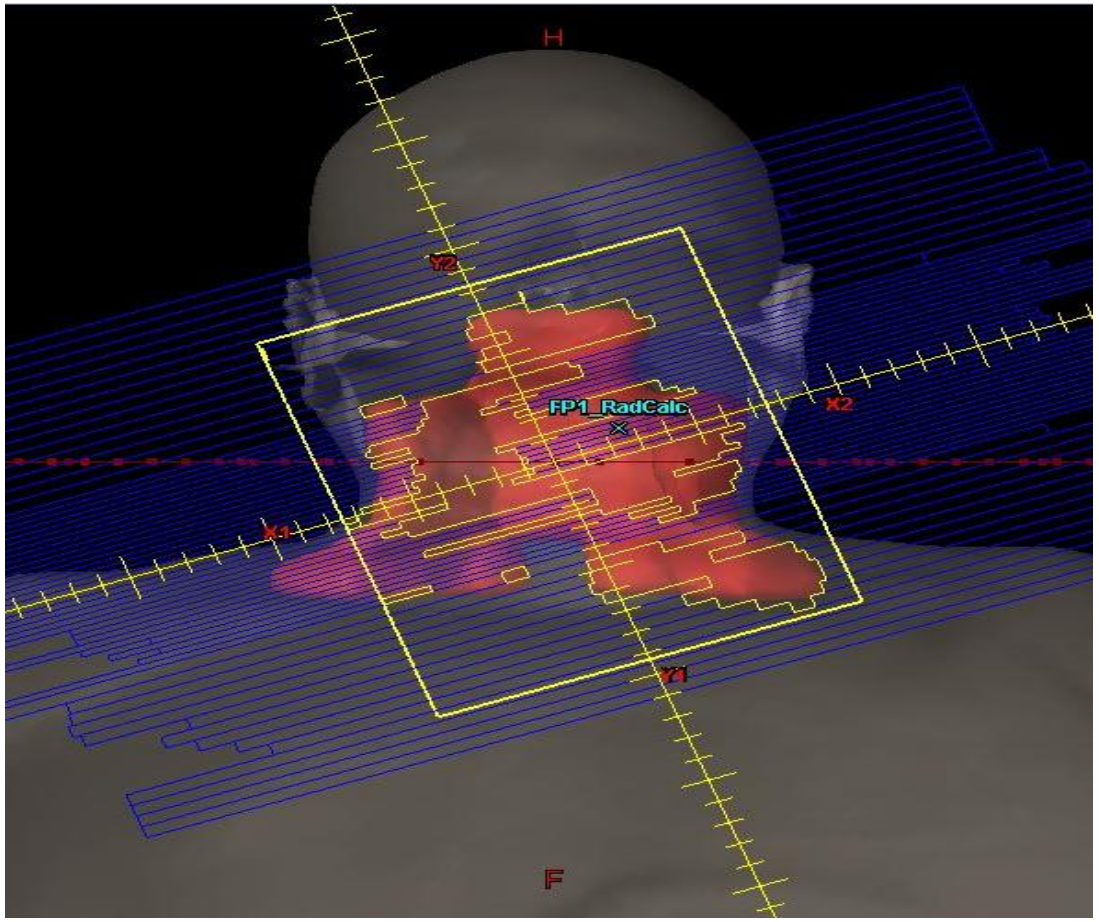
VMAT Optimization (Varian)

- Optimization performed in 4 resolution levels, each level is divided into steps.
  - 178 control points used throughout the optimization (no longer progressive resolution levels)
  - Initial MLC shapes conform to target
  - Initial dose rates equal for all segments
  - Larger changes are made in earlier levels
  - Number of calculation directions doubles at each resolution level.
- Fluence is optimized first and then mechanical limits are enforced in later steps

From Otto. Med Phys. 2008.

Image courtesy of Varian Medical Systems

VMAT Control Points



MLC Properties

General | Control Points | Leaf Positions | Debug

Index	Meterset Weight	Gantry Rtn [deg]	Dose Rate [MU/min]	Gantry Speed [deg/s]	MU/deg
145	0.8179	247.1	132.028	4.800	0.458
146	0.8232	245.1	119.501	4.800	0.415
147	0.8284	243.0	119.501	4.800	0.415
148	0.8337	241.0	119.501	4.800	0.415
149	0.8389	239.0	119.501	4.800	0.415
150	0.8451	236.9	142.050	4.800	0.493
151	0.8514	234.9	142.050	4.800	0.493
152	0.8576	232.9	142.050	4.800	0.493
153	0.8638	230.8	142.050	4.800	0.493
154	0.8694	228.8	127.183	4.800	0.442
155	0.8750	226.8	127.183	4.800	0.442
156	0.8806	224.7	127.183	4.800	0.442
157	0.8862	222.7	127.183	4.800	0.442
158	0.8916	220.7	123.590	4.800	0.429
159	0.8970	218.6	123.590	4.800	0.429
160	0.9024	216.6	123.590	4.800	0.429
161	0.9079	214.6	123.590	4.800	0.429
162	0.9134	212.5	125.774	4.800	0.437
163	0.9189	210.5	125.774	4.800	0.437
164	0.9244	208.5	125.774	4.800	0.437
165	0.9299	206.4	125.774	4.800	0.437
166	0.9354	204.4	125.661	4.800	0.436
167	0.9410	202.4	125.661	4.800	0.436
168	0.9465	200.3	125.661	4.800	0.436
169	0.9520	198.3	125.661	4.800	0.436
170	0.9577	196.3	130.216	4.800	0.452
171	0.9634	194.2	130.216	4.800	0.452
172	0.9691	192.2	130.216	4.800	0.452
173	0.9748	190.2	130.216	4.800	0.452
174	0.9804	188.1	126.464	4.800	0.439
175	0.9859	186.1	126.464	4.800	0.439
176	0.9915	184.1	126.464	4.800	0.439
177	0.9970	182.0	126.464	4.800	0.439
178	1.0000	181.0	134.746	4.800	0.468

RaySearch/Philips Smart Arc Optimization

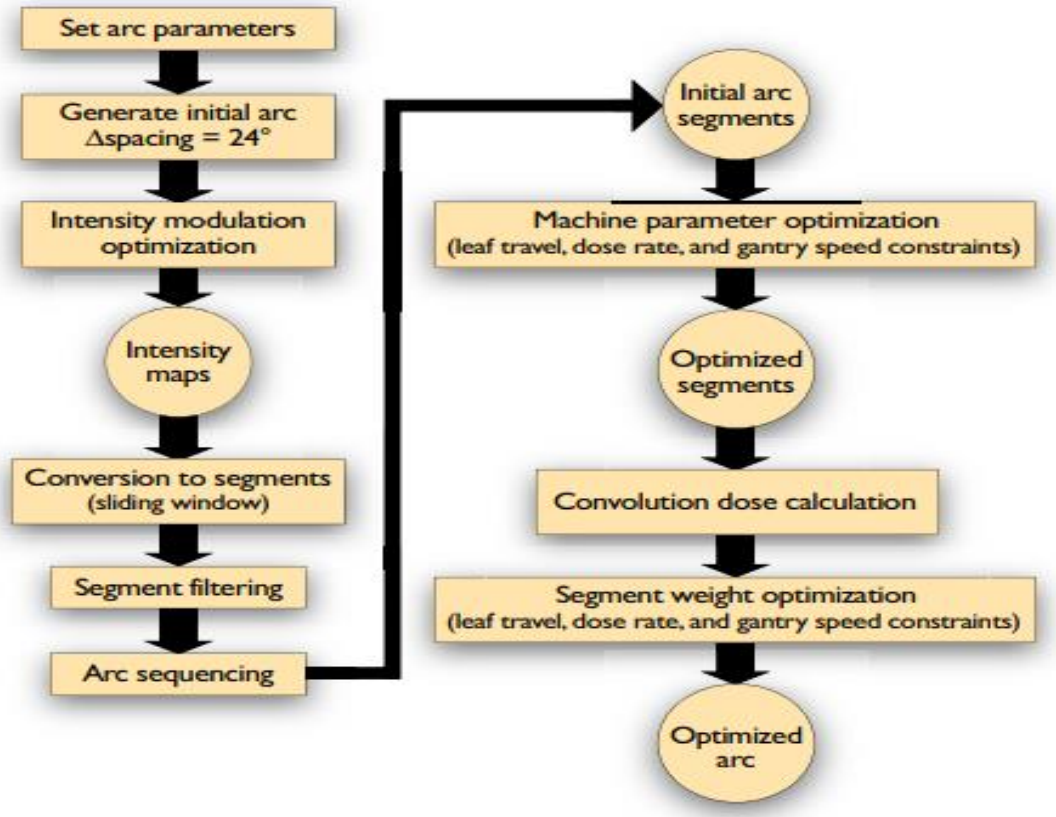


Figure 1: The dynamic arc optimization process

From Pinnacle^3 SmartArc White Paper

Smart Arc Leaf Sequencing

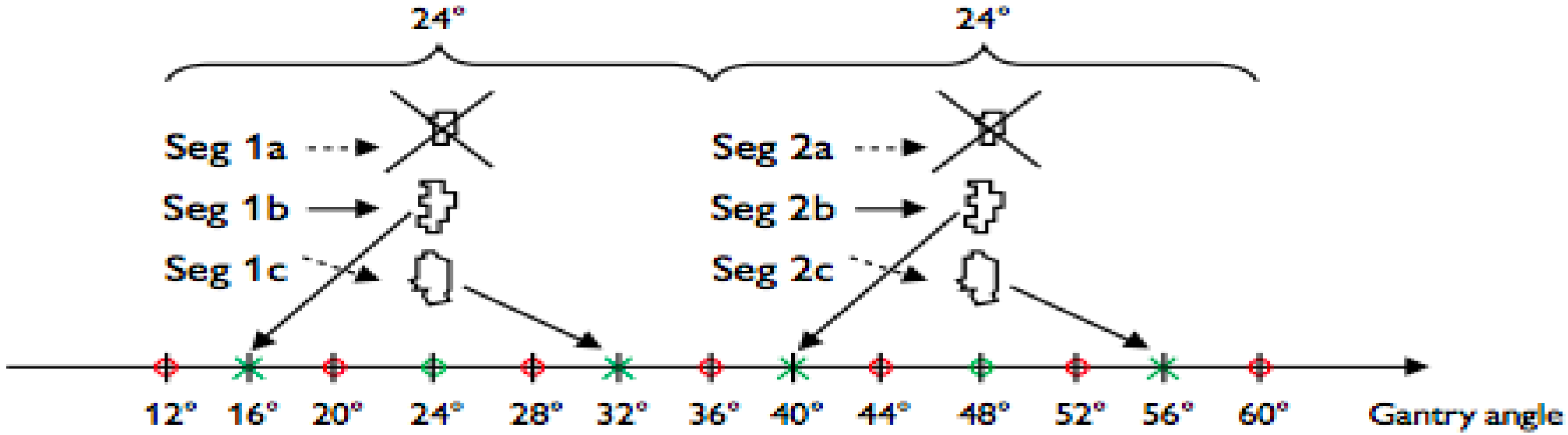


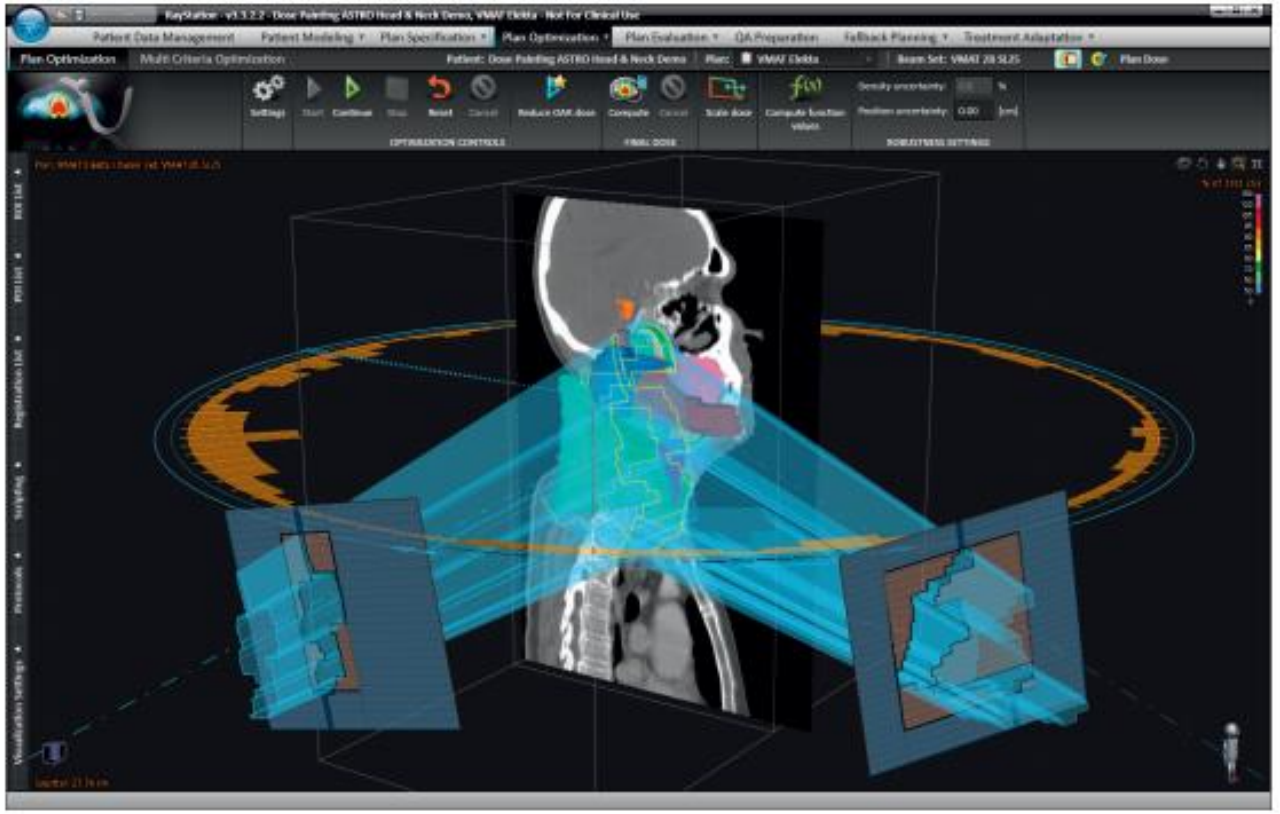
Figure 2: Segment filtering and redistribution. The optimized fluences at the initial directions of 24° and 48° are converted into three control points, respectively, where one segment is discarded and two are repositioned (crosses). Additional control points are created by linear interpolation of the leaves (light circles). The green control points are chosen for subsequent optimization. Another set of control points is introduced (dark circles) such that the final gantry spacing is 4°. The leaf positions and dose rates for these control points are not variables in the optimization; instead they are regenerated using interpolation every time dose or gradients are to be computed.

From Pinnacle[3] SmartArc White Paper.
See also Bzdusek K, Kaus M, Schewe J, Beckett L, and Meltsner M. An efficient approach To volumetric modulated arc therapy optimization and sequencing. Med. Phys. 35 (6), 2867-2867 (2008).

Multiple Arcs

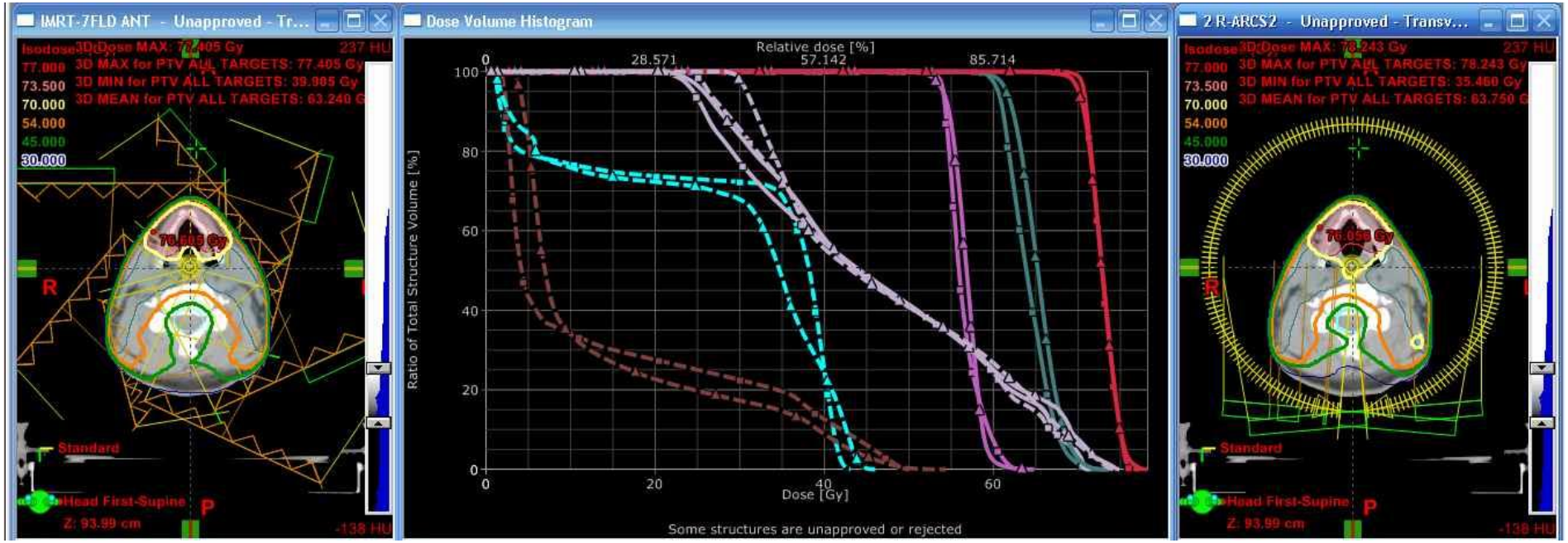
- RayStation has two ways to optimize multiple arcs.
- Multiple Arcs
  - Fluence maps can be similar if two arcs cover the same beam angles
  - Limit jaw motion
- Dual Arc
  - Second arc is created during sequencing
  - Process similar to previous except that there are more initial fluence maps and they are distributed between the arcs
  - Generally produced 2 arcs treating two different sides of the target (right and Left)

Simultaneous optimization of two arcs using the dual arc feature



From RaySearch White Paper. VMAT Optimization in RayStation.
See also K. Bzdusek, H. Friberger, K. Eriksson, B. Hårdemark, D. Robinson, M. Kaus. Development and evaluation of an efficient approach to volumetric arc therapy planning, Medical Physics 36(6):2328-39, 2009.

Comparison of VMAT to Static Field IMRT

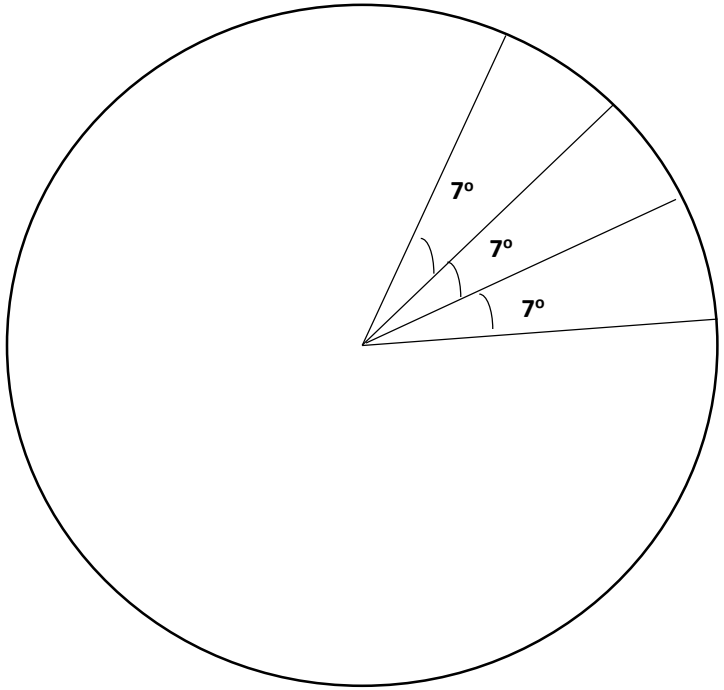


Static Field IMRT: 1260 MU

Squares: Static Field
Triangles: Rapidarc

RapidArc: 588 MU

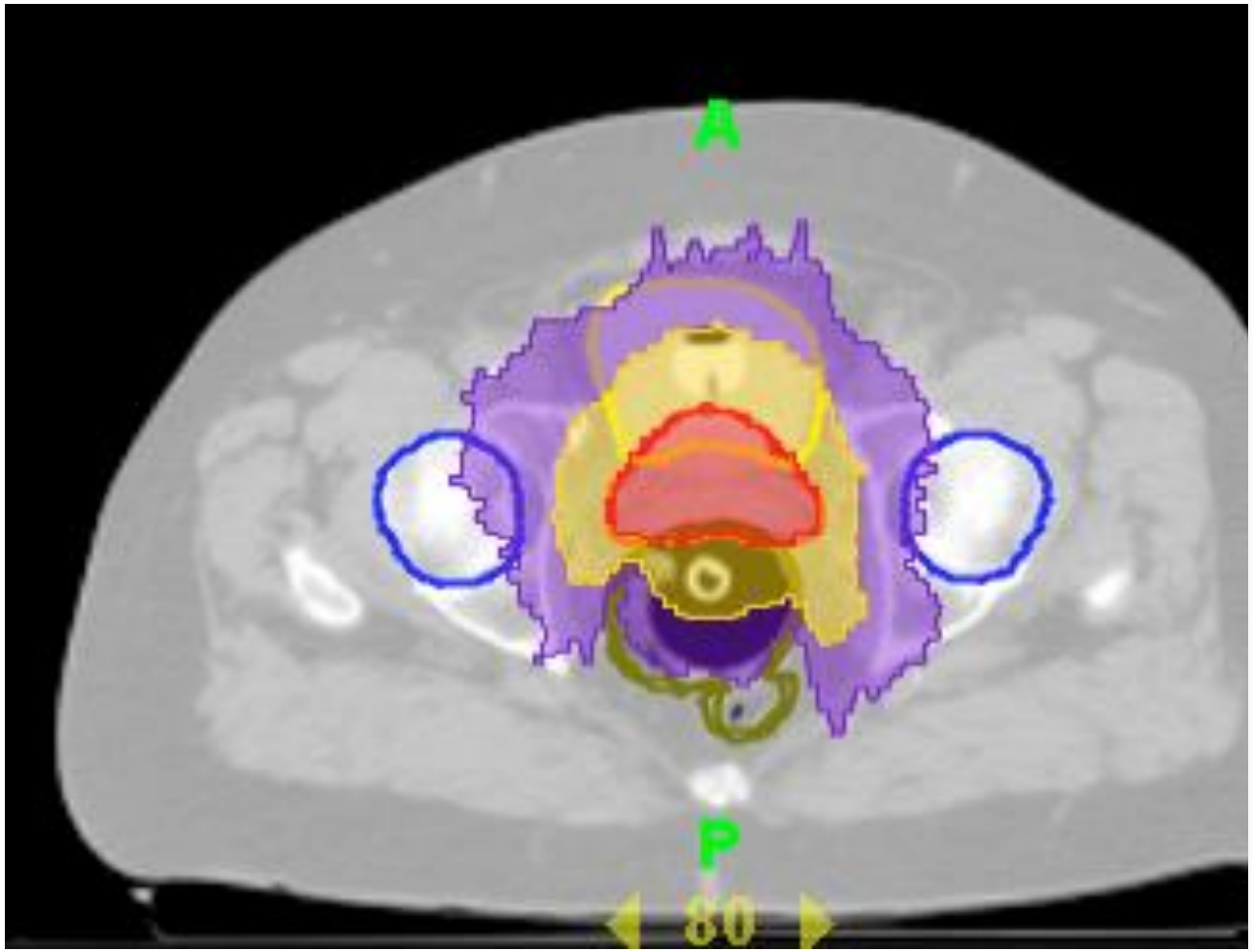
Arc Sampling Tomotherapy

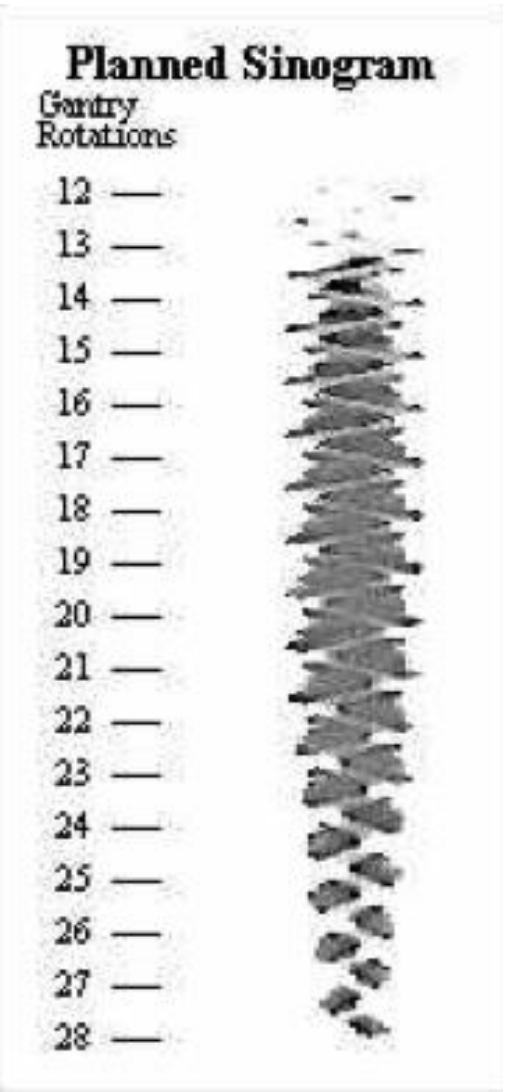


- Rotation modeled as 51 static beams for optimization
- 153 beams for dose calculation for improved delivery accuracy
- C/S based dose calculation

Hardcastle et al. MedPhys 39, 4788-4794. 2012

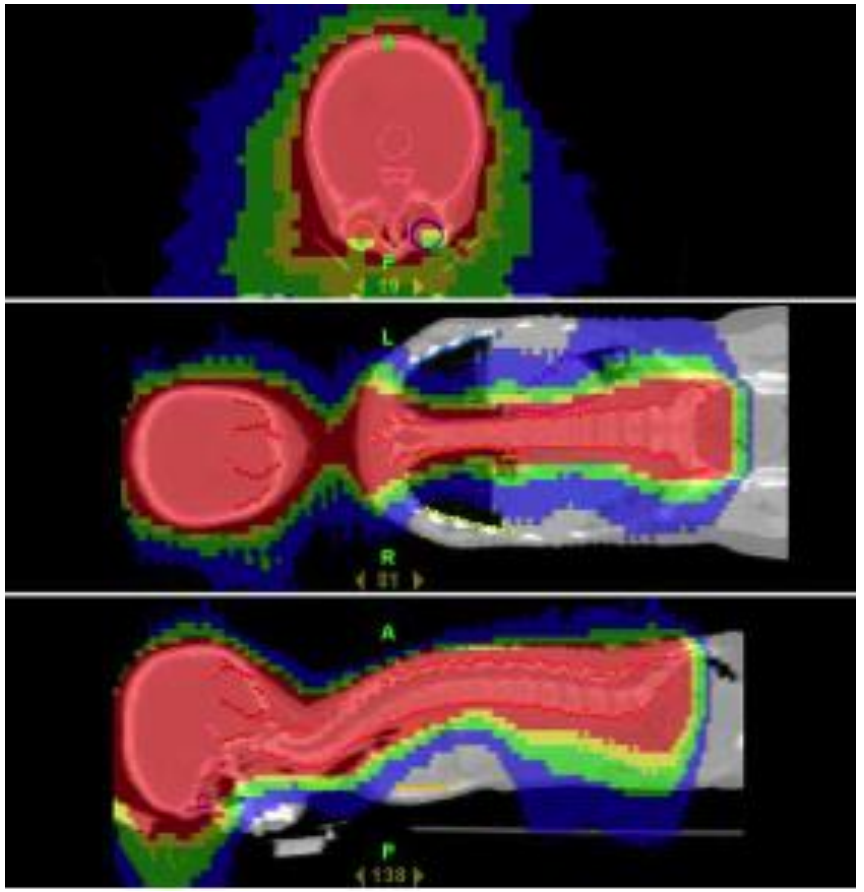
Tomotherapy Leaf Sequencing





Comparison of Tomotherapy to VMAT

- Similar quality dose distributions
- Longer planning and delivery time
- Tomotherapy will be easier to optimize for very complex targets and target that exceed the maximum field length/width for VMAT



Pen˜agarı´canoe et. al. Radiotherapy and Oncology. 2005

Summary

- The basics of IMRT where presented
- In the next lecture, we will talk about practical tips for treatment planning