Physical Aspects of IMRT

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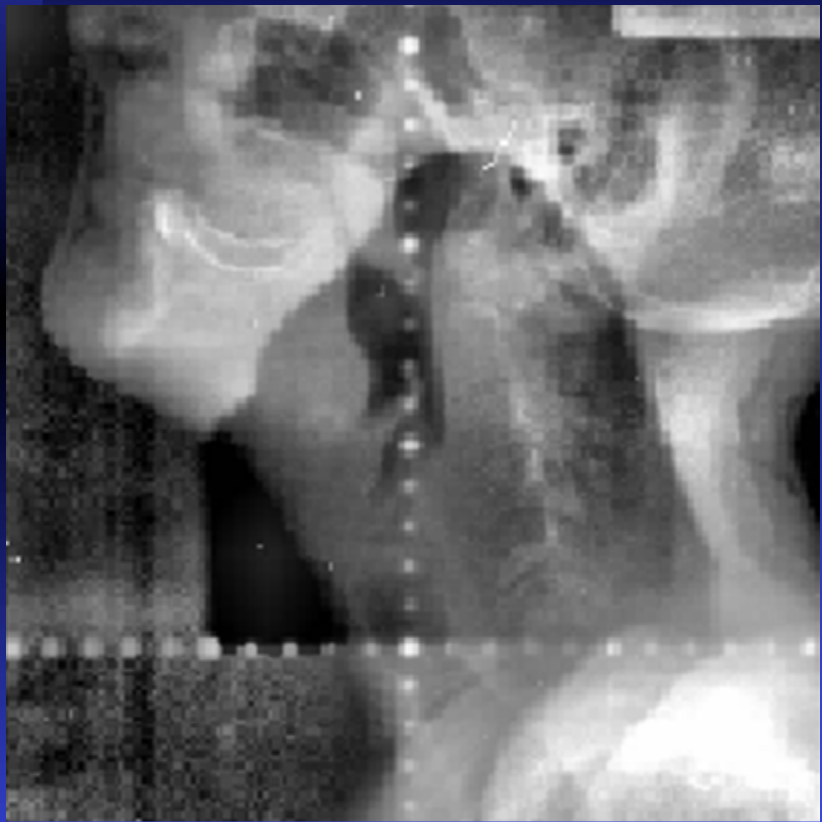
3D/IMRT Comparison



IMRT Techniques

- Conventional – Beam modifiers (wedge, partial blocks)
- Compensators – LINAC, Proton therapy
- Computerized MLCs – LINAC
- Binary MLCs – PEACOCK, Tomotherapy
- Robot-Controlled – Cyberknife
- Scanning Beams – Proton therapy (IMPT)

IMRT Delivery

- Step and Shoot

MLC Step and Shoot Demo.mp4

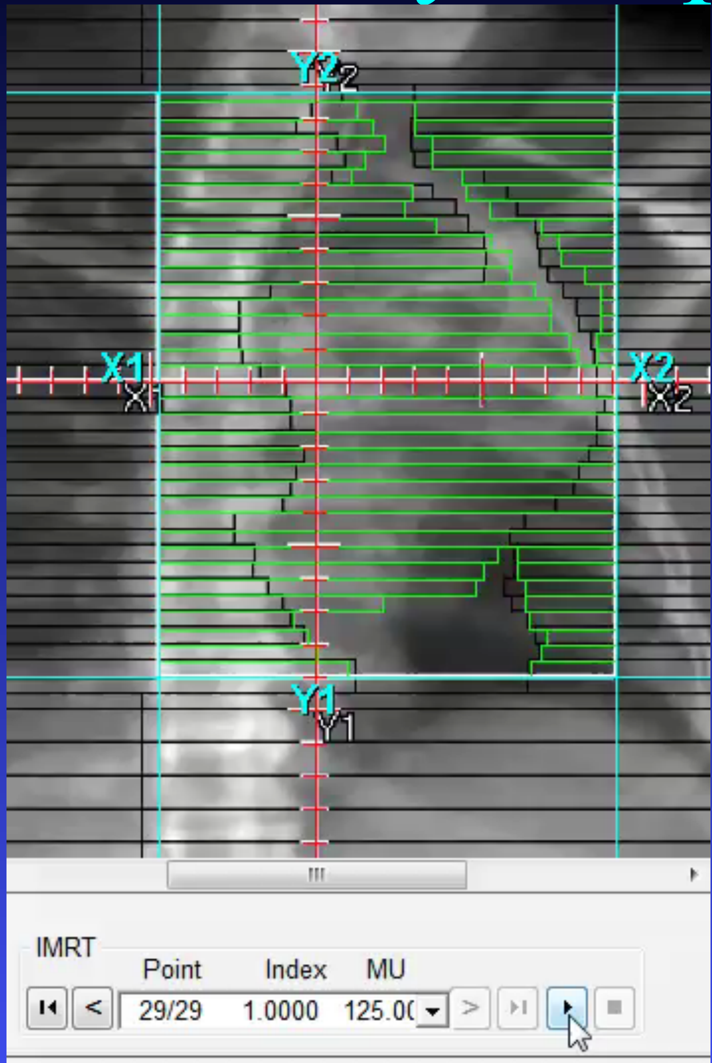
- Sliding Window

Sliding Window Demo.mp4

- VMAT

VMAT Dynamic Demo.mp4

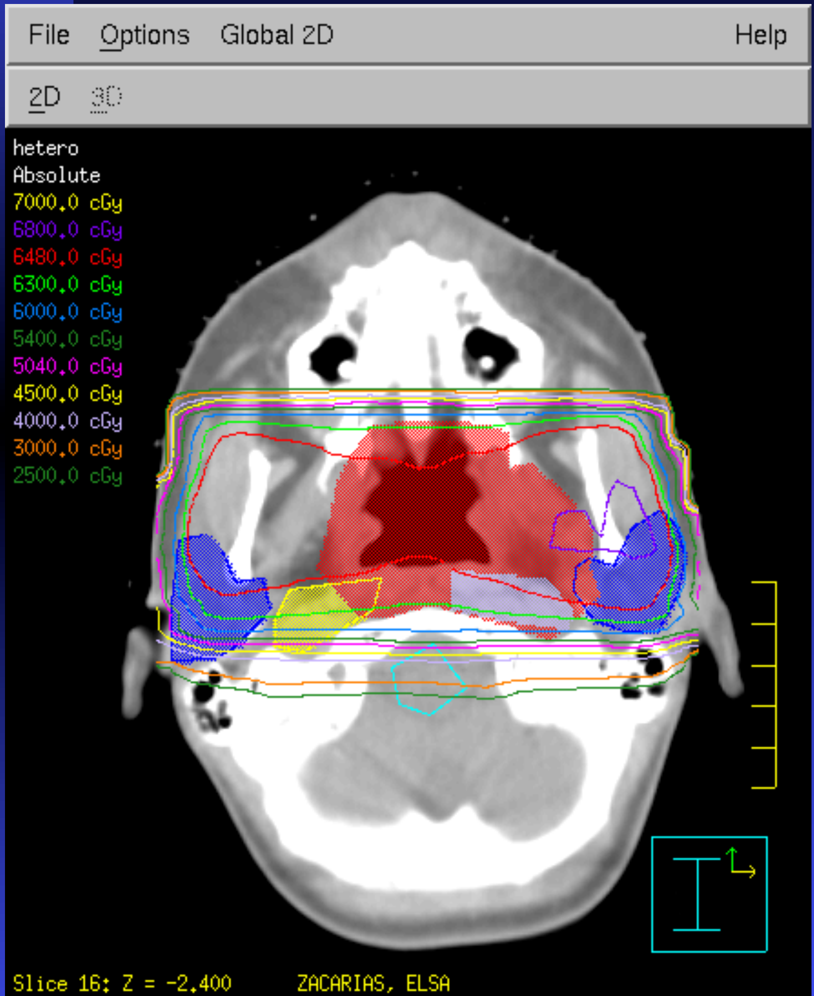
IMRT Delivery: Step and Shoot

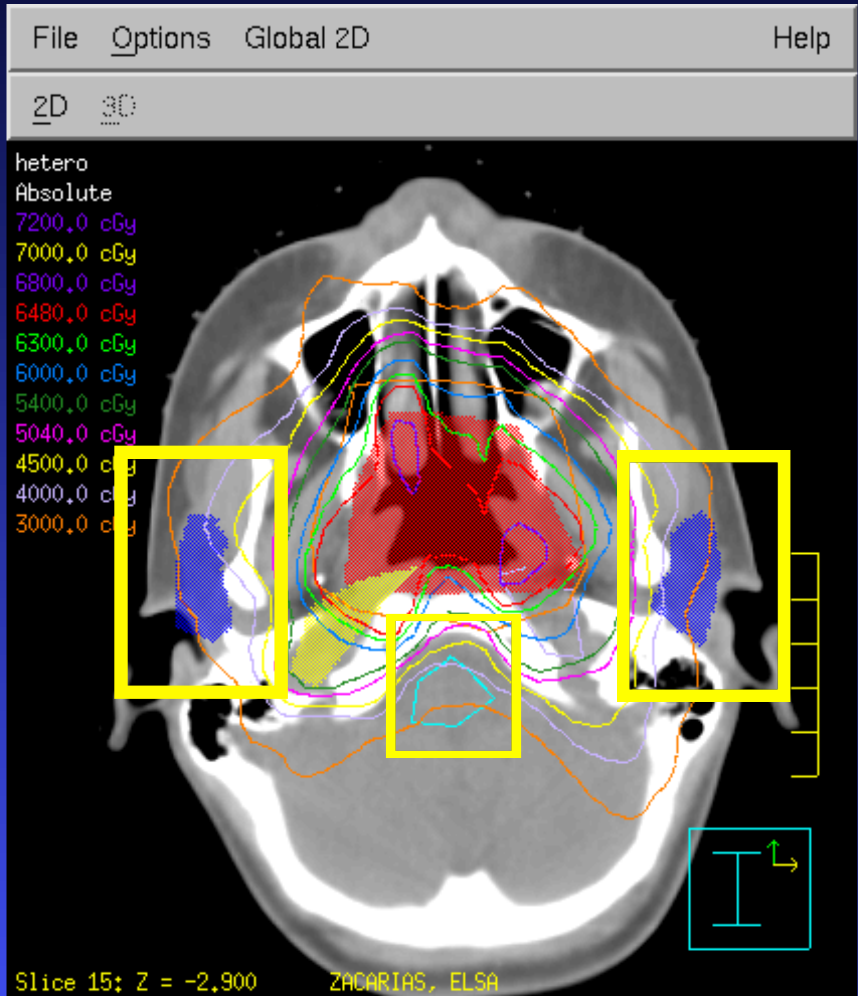


IMRT Delivery: Sliding Window

IMRT Delivery : VMAT

Motivation?


File Options Global 2D Help
2D 3D
hetero
Absolute
7000.0 cGy
6800.0 cGy
6480.0 cGy
6300.0 cGy
6000.0 cGy
5400.0 cGy
5040.0 cGy
4500.0 cGy
4000.0 cGy
3000.0 cGy
2500.0 cGy
Slice 16: Z = -2.400
ZACARIAS, ELSA


File Options Global 2D Help
2D 3D
hetero
Absolute
7200.0 cGy
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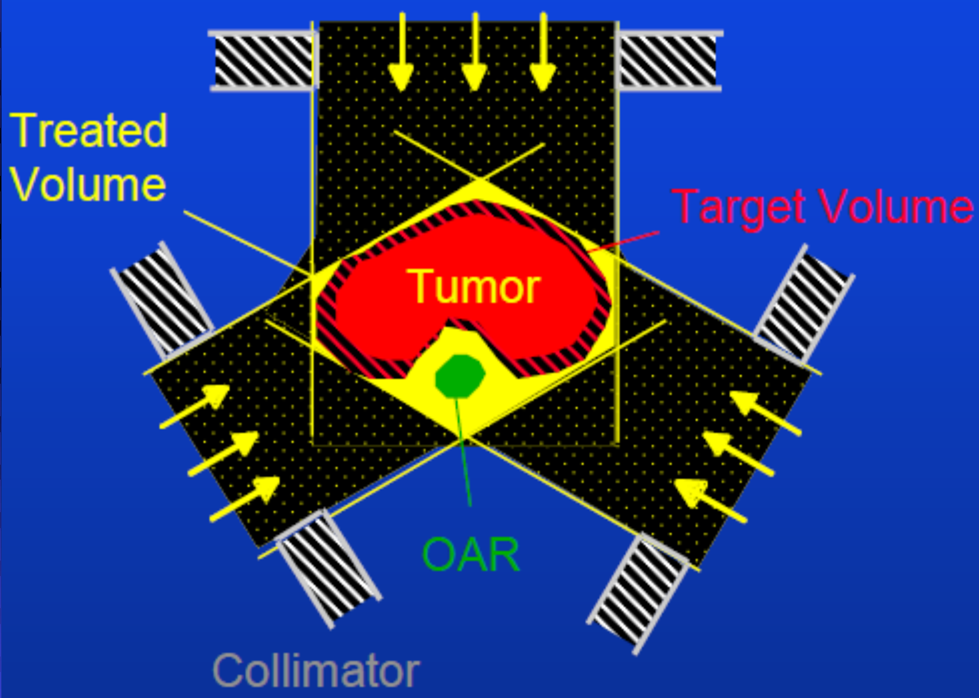
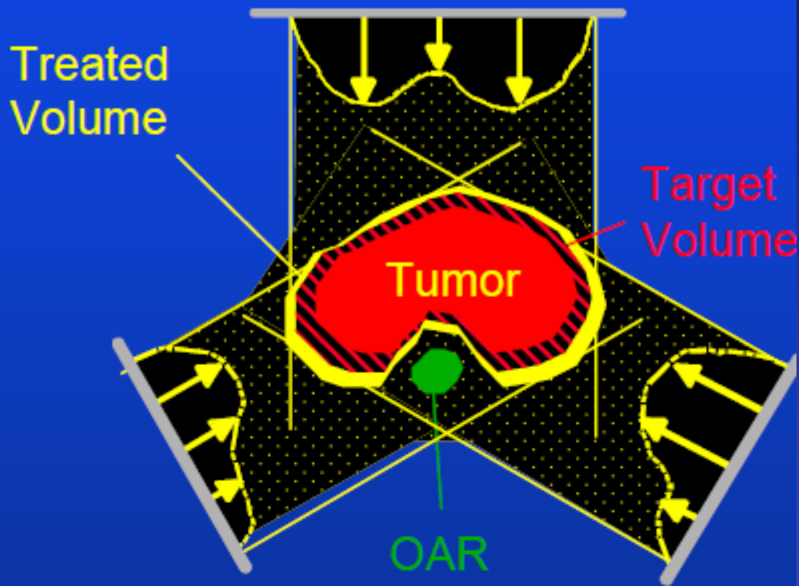
6800.0 cGy
6480.0 cGy
6300.0 cGy
6000.0 cGy
5400.0 cGy
5040.0 cGy
Slice 15: Z = -2.900
ZACARIAS, ELSA

Motivation

3D conformal Rx



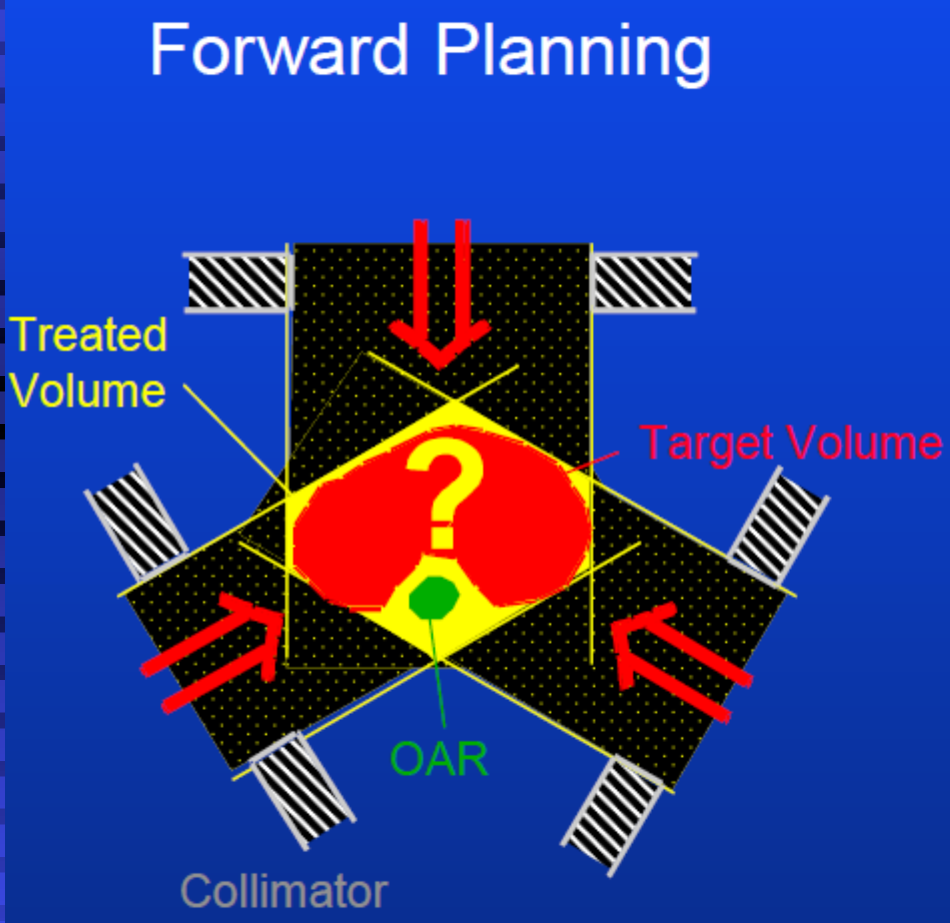
Intensity Modulation

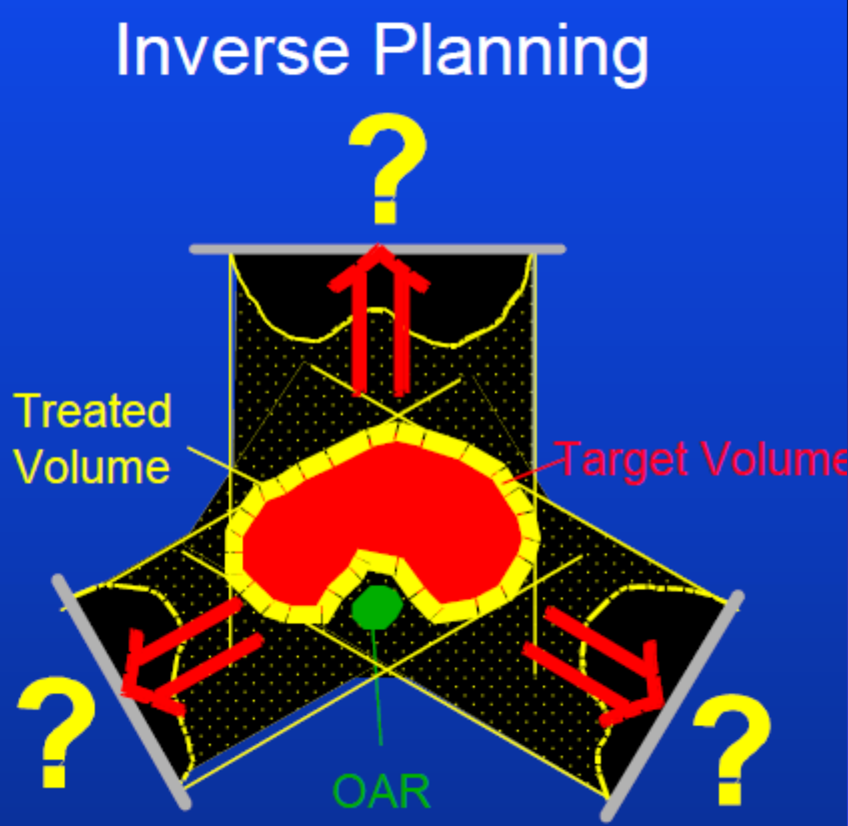


Thomas Bortfeld et al.

Benefits of Using IMRT

- Dose reductions to normal tissue
- Dose Escalation to target structures
- Improves target coverage of complex tumor shapes, e.g. tumor wraps around brainstem or spinal cord
- Ability to delivers different doses to different targets
- Ideal for reducing doses to critical structures





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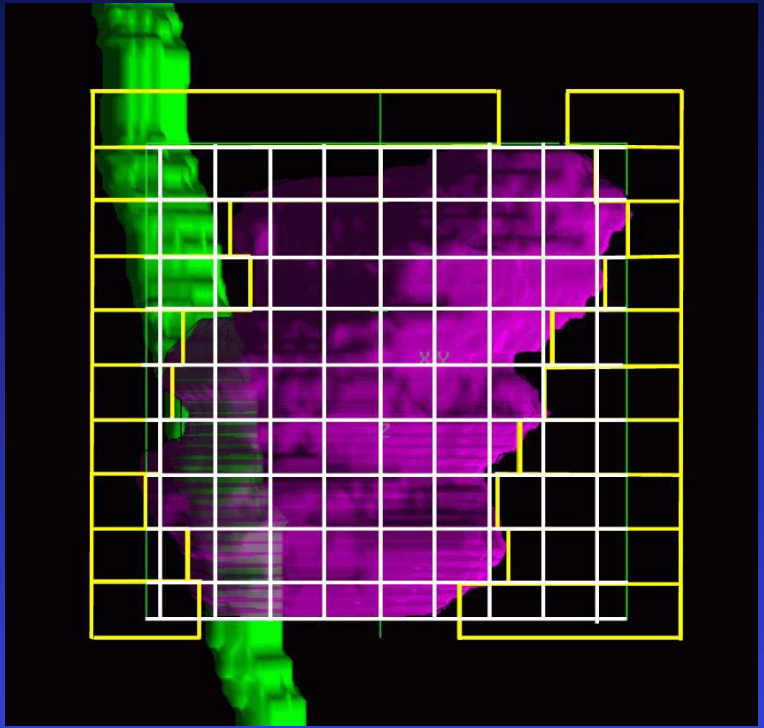
IMRT Inverse Planning

- Optimization Process for Fixed Field IMRT
  - Beamlet Based Optimization
  - Direct Aperture Optimization (DAO)

The Beamlet Model

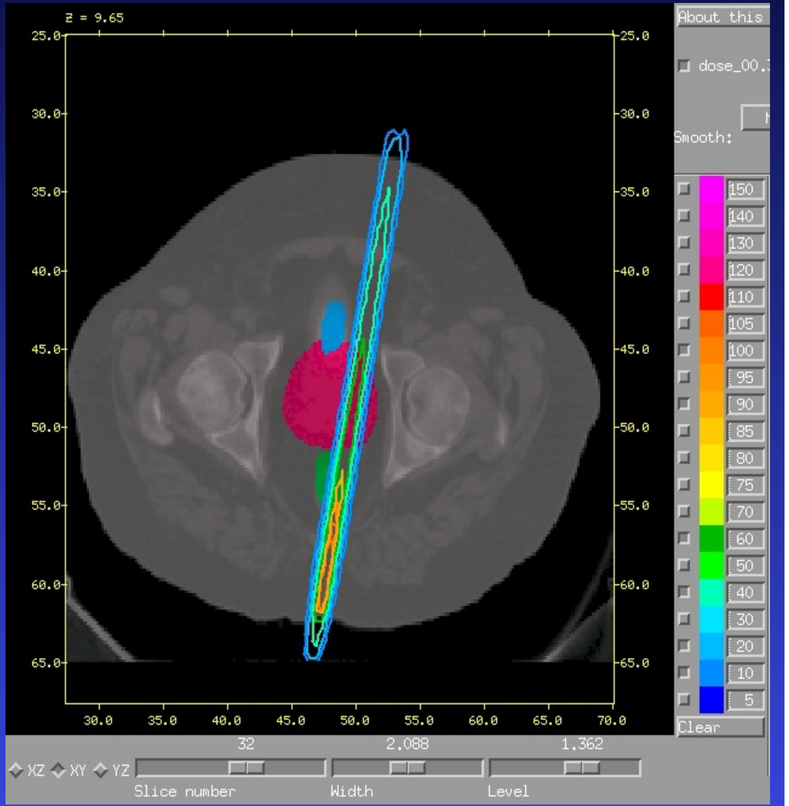
- Before an IMRT optimization, each beam is defined and divided into a number of smaller beamlets (pencil beams), usually 5 mm x 5 mm



The Beamlet Model

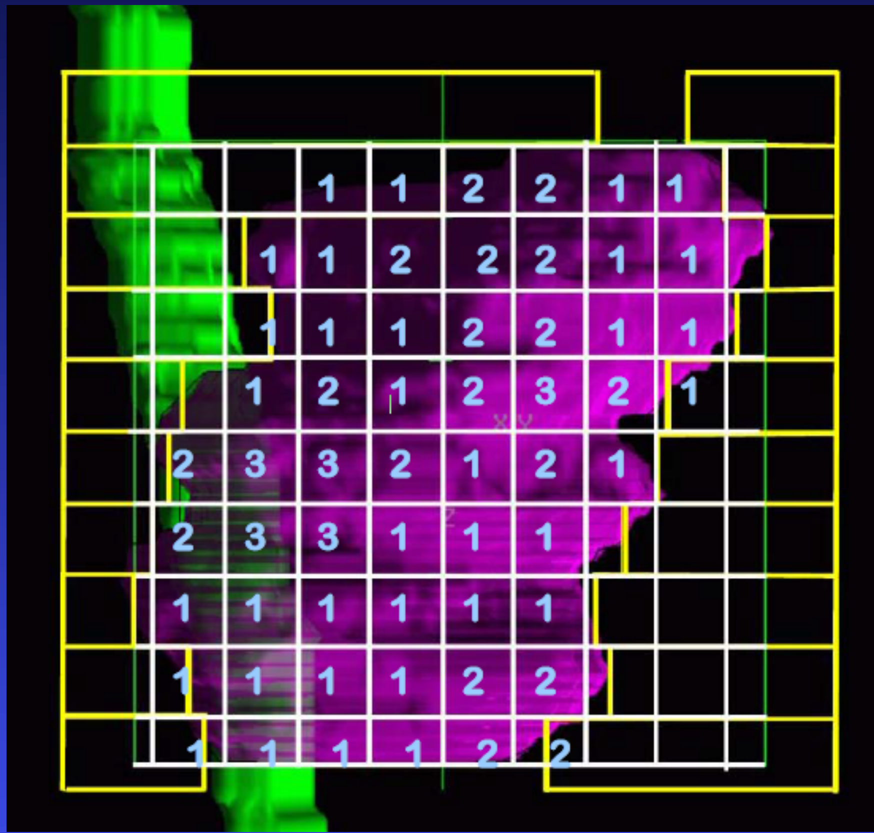
- The corresponding dose distributions from all beamlets are computed and added together.

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



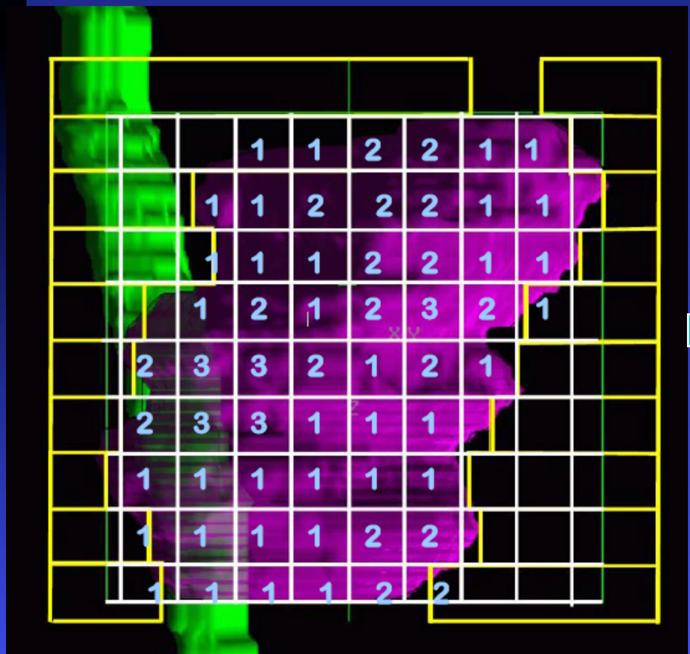
The Beamlet Model

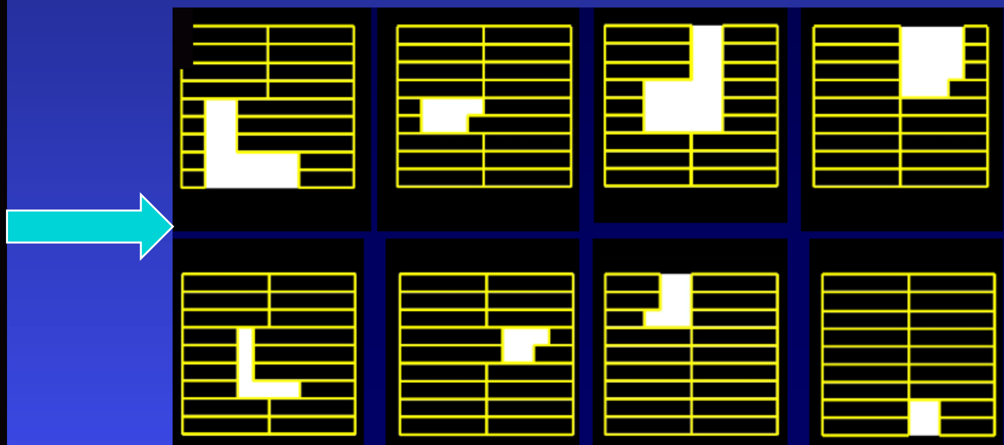
- Beamlet weights are optimized to produce an optimized fluence map or matrix for each beam direction.



The Beamlet Two-Steps Model

- Leaf Sequencing: From “ideal” fluence, the “deliverable” MLC patterns are generated map base on machine characteristics.





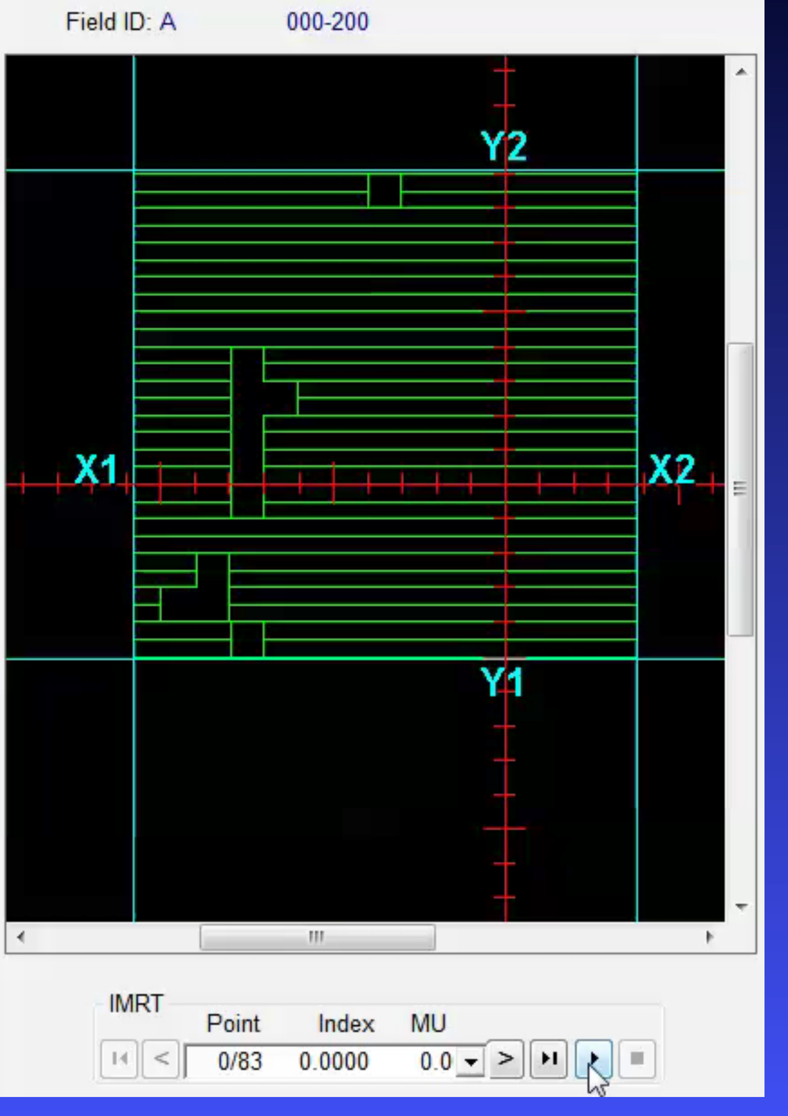
The Beamlet Two-Steps Model

- The final “full” dose is calculated from all small beam segments (control points)
  - Requires a large number of segments in order to simulate the “ideal” map
  - Small field segments cause significant degradation in the plan quality
  - What you see from “ideal” fluence is “NOT” what you get from small fields

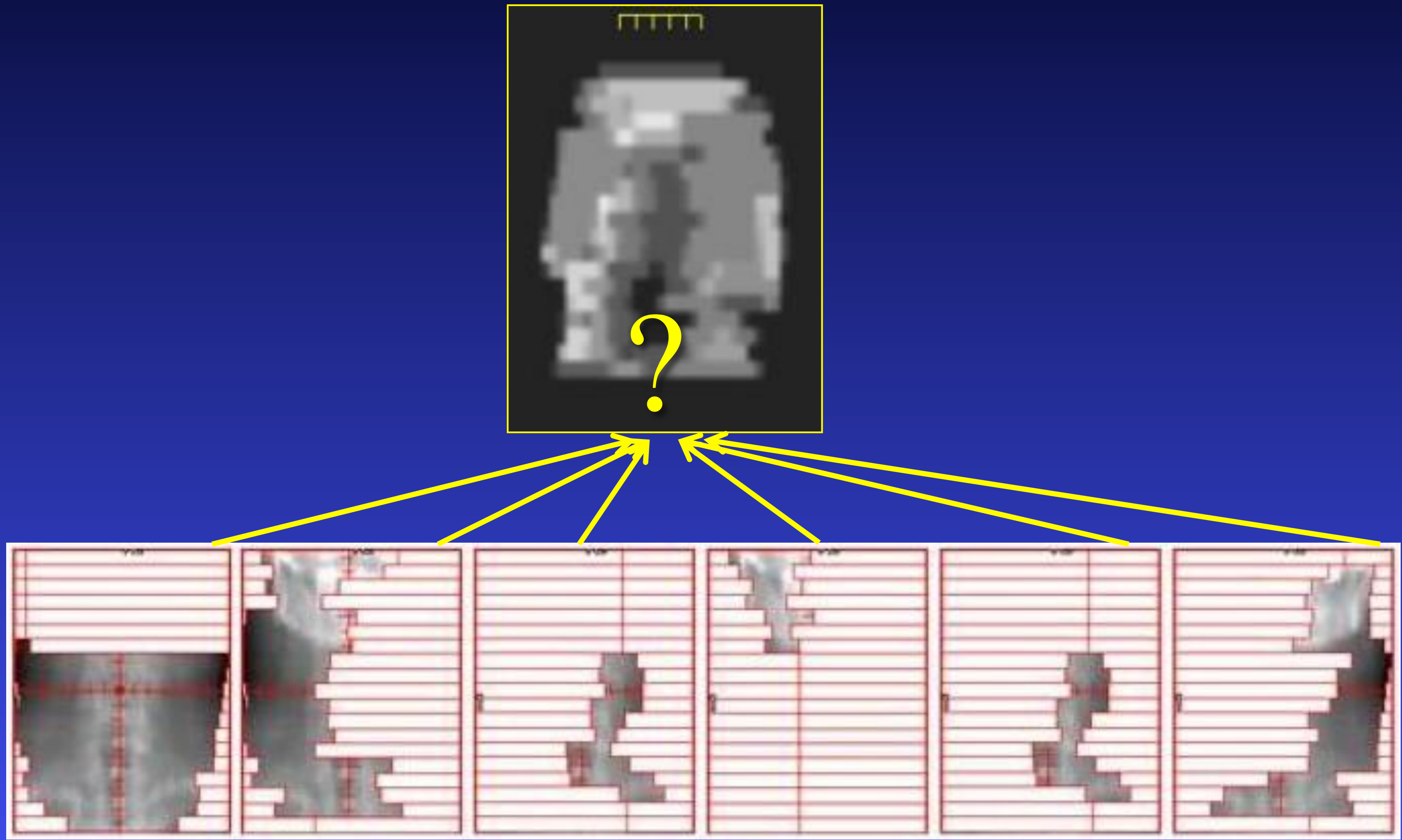
NOMOS CORVUS Plan (2002)

CORVUS Demo.mp4

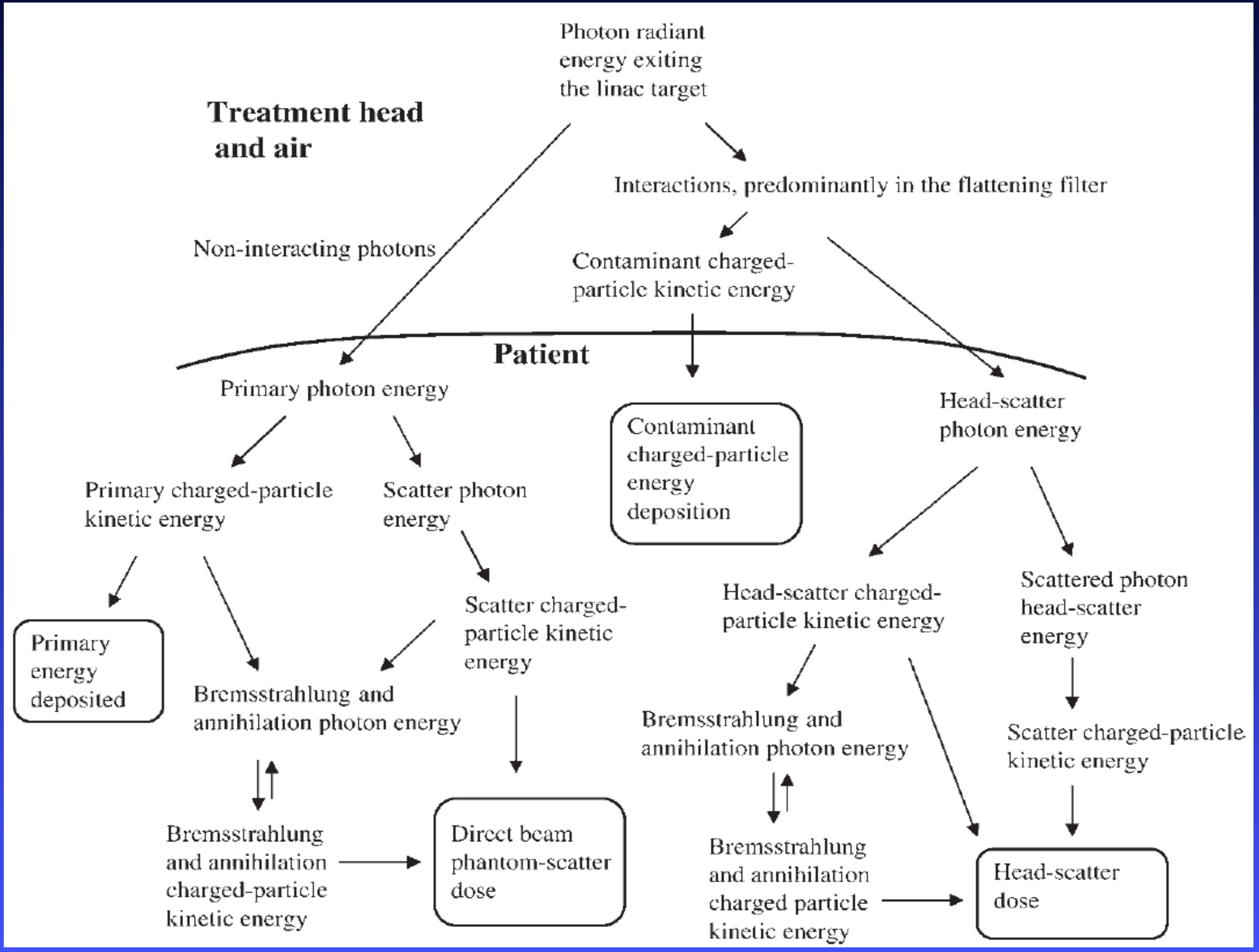
NOMOS CORVUS Plan (2002)



IMRT Dosimetry - Small Fields



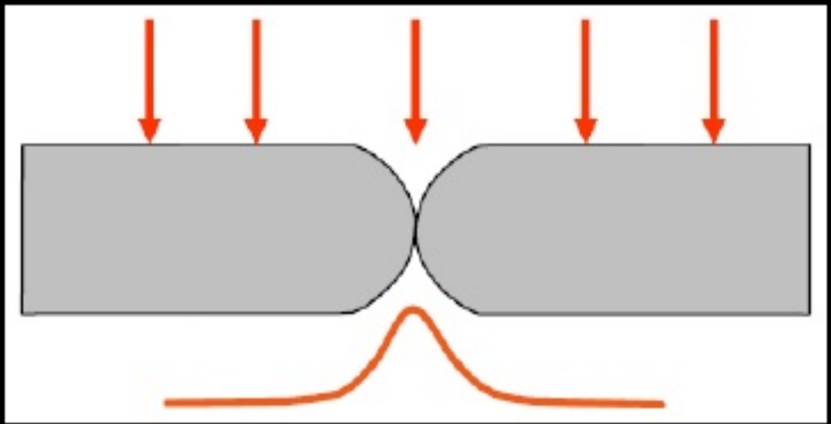
Dose Modeling Problem



Dose Modeling Problem

IMRT – MLC dosimetric leaf gap

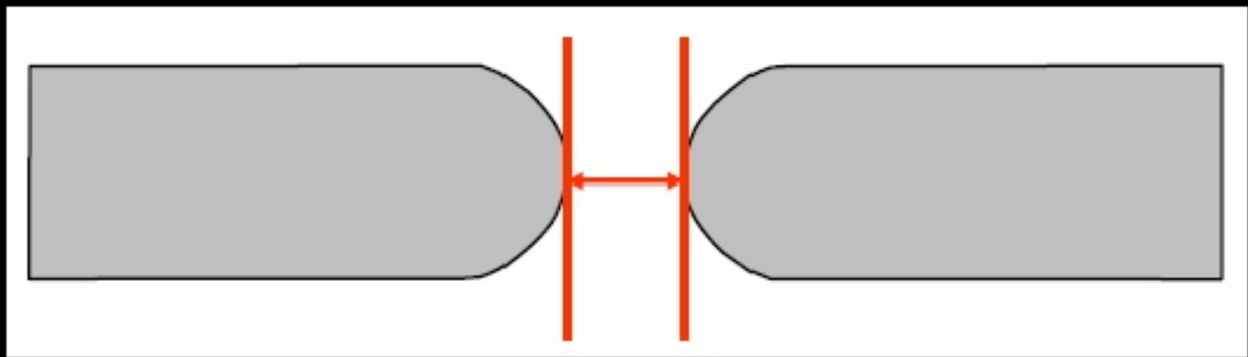
- Accounts for extra transmission through the rounded leaf edge
  - Modeled as an apparent gap between two closed straight edge leaves



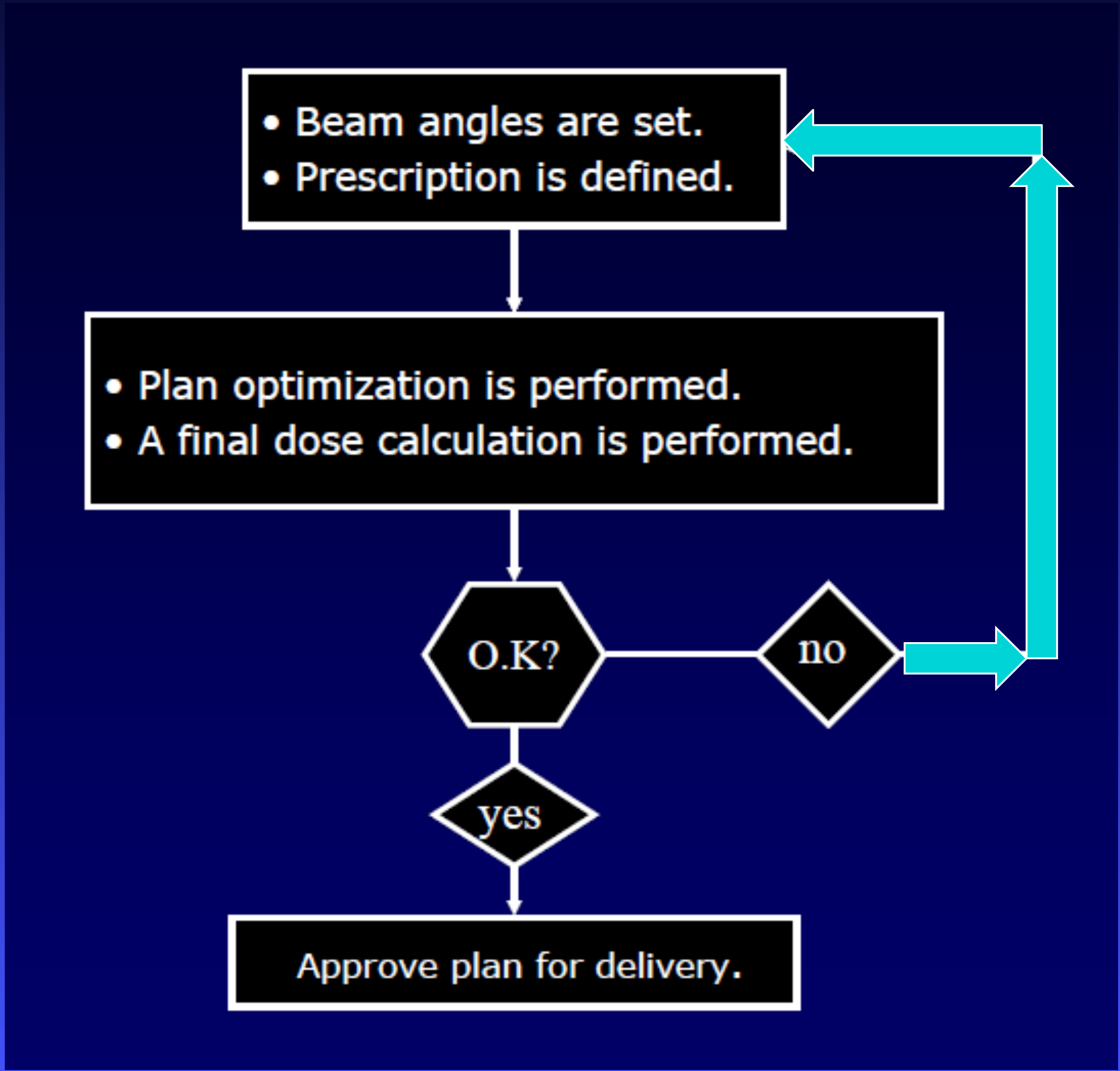
Dose Modeling Problem

IMRT – MLC minimum dose dynamic leaf gap

- Minimal tip to tip distance which needs to be maintained for any moving leaf pair in the dMLC mode



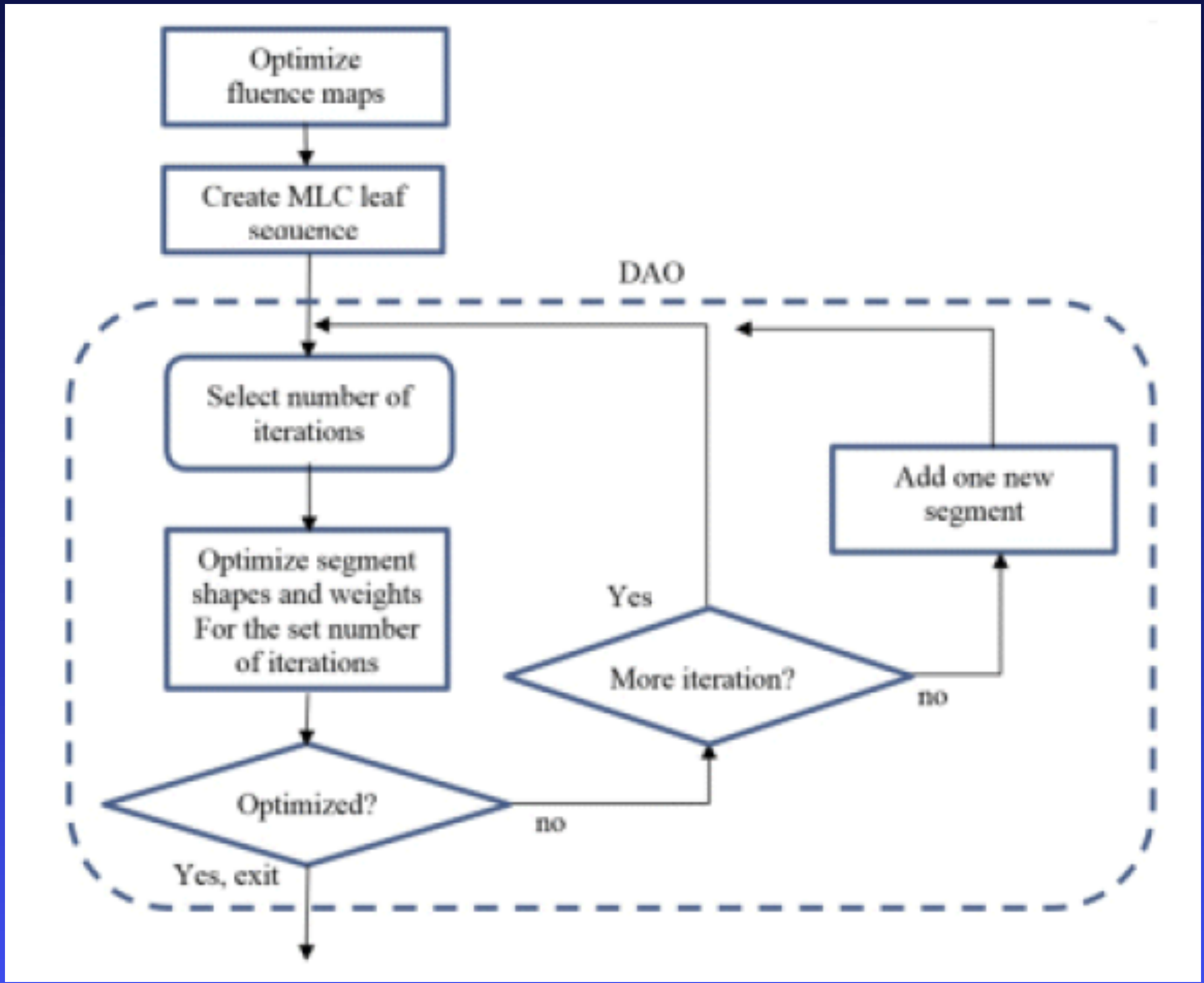
IMRT Planning Process



The Beamlet Two-Steps Model

- 1^{st} Generation IMRT was adopted by nearly all TPS in1990:
  - Corvus (NOMOS) – Sliding Window
  - Pinnacle (ADAC) – Step and Shoot
  - Eclipse (Varian) – Sliding Window
  - Plato (Nucletron)
  - Xio (CMS)

Direct Aperture Optimization (DAO)



Direct Aperture Optimization (DAO)

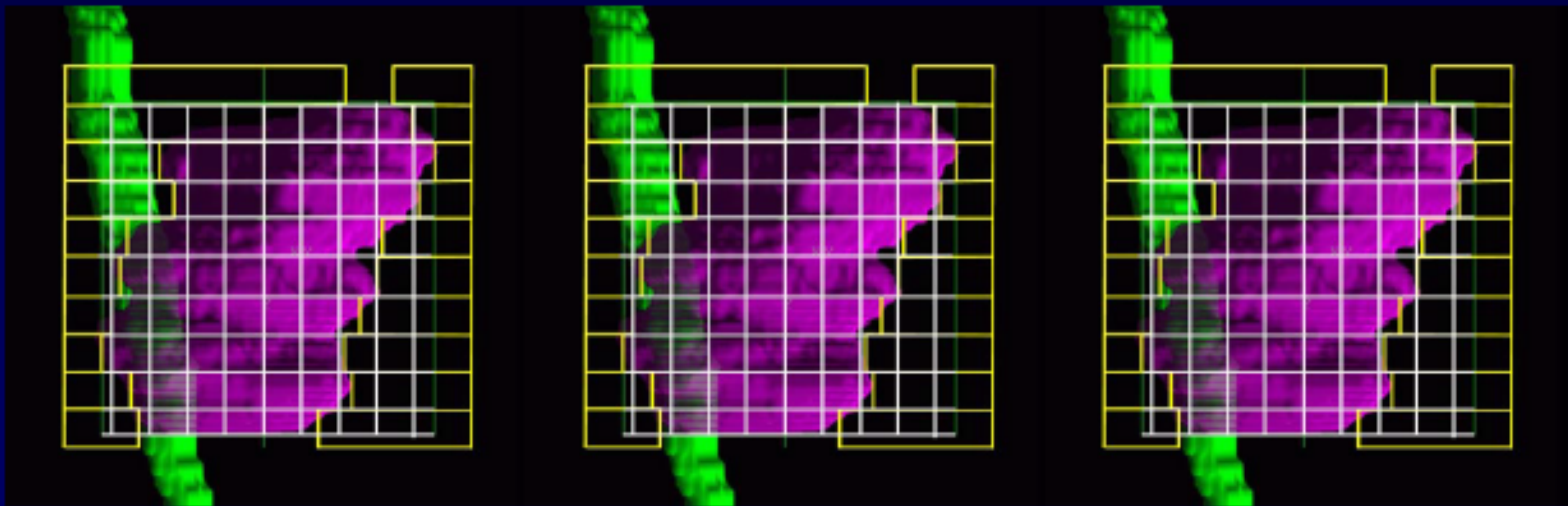
- Inverse planning technique where both the beam shapes and the beam weights are optimized at the same time
- All of the MLC delivery parameters are included in the optimization (DMPO)
- Number of beam segments and minimum MU per segment can be also predefined

DAO 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



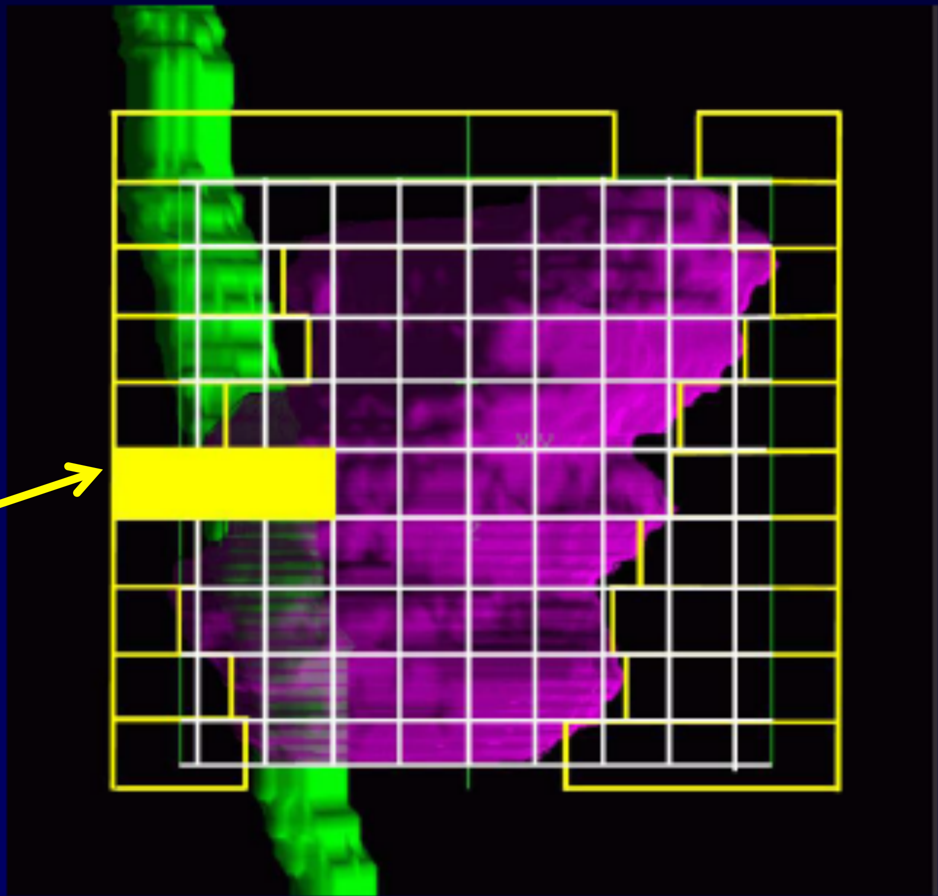
Pick an Parameter and Make a Change

Aperture 1

Leaf pair 6

Left leaf position

Move leaf in **1 cm**



Keep or Reject the Change

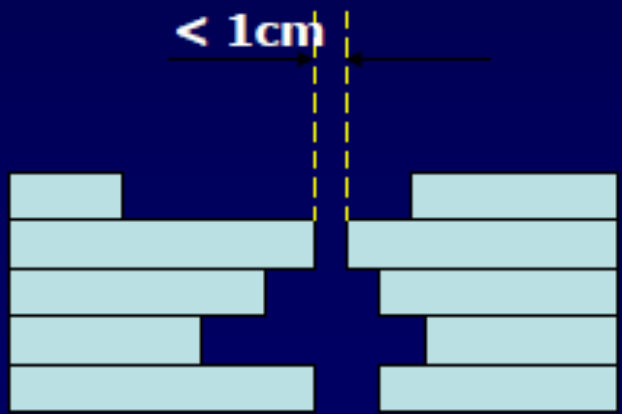
Based on:

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

MLC Constraints

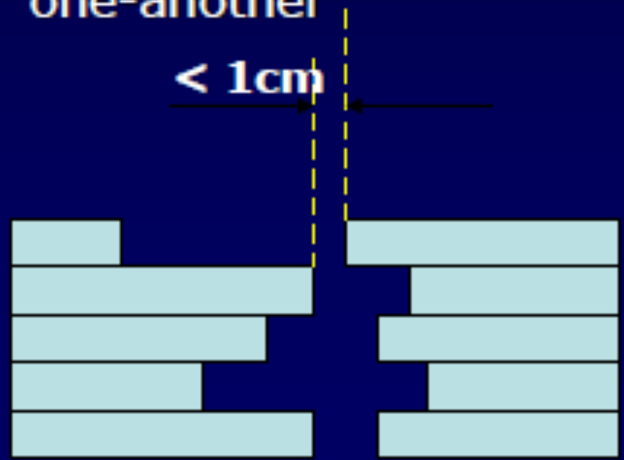
Some sample Elekta constraints:

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



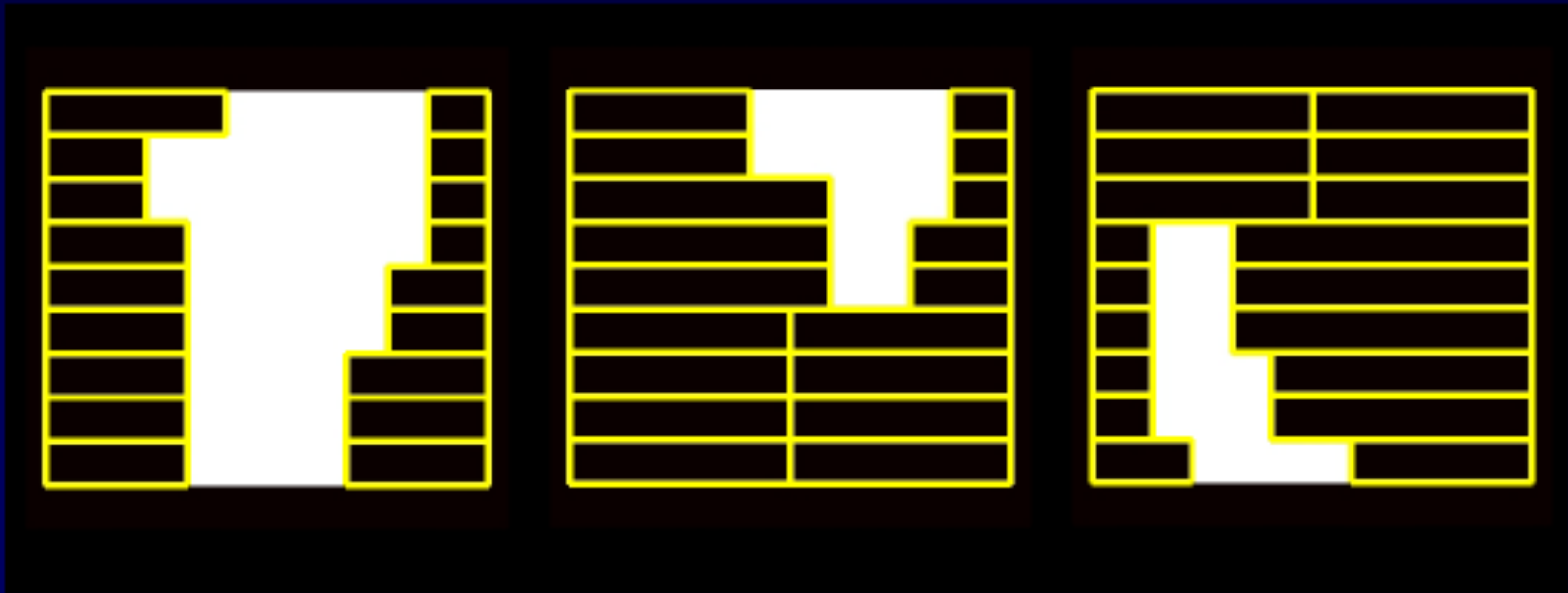
Not allowed

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



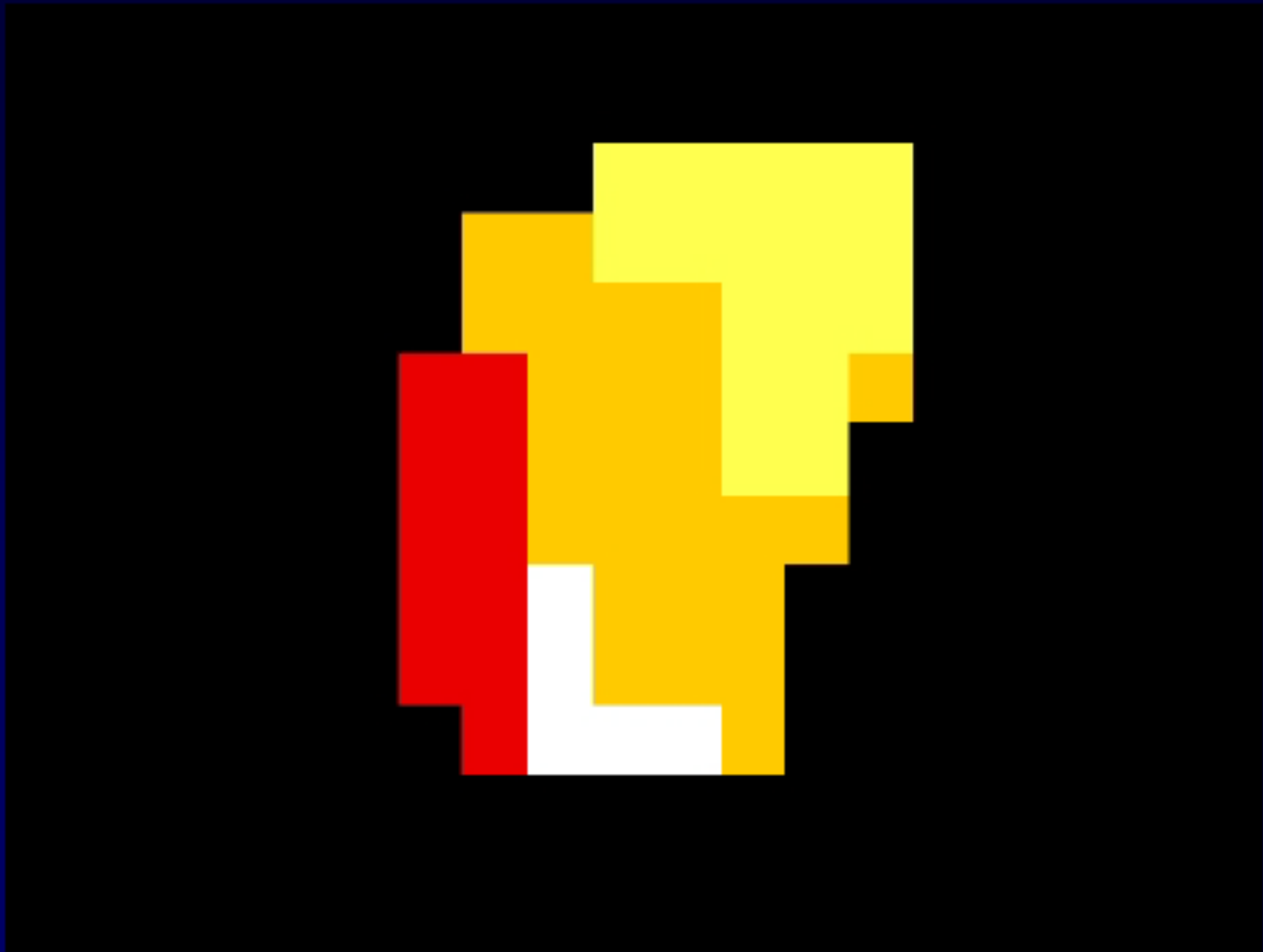
Not allowed

After numerous iterations...



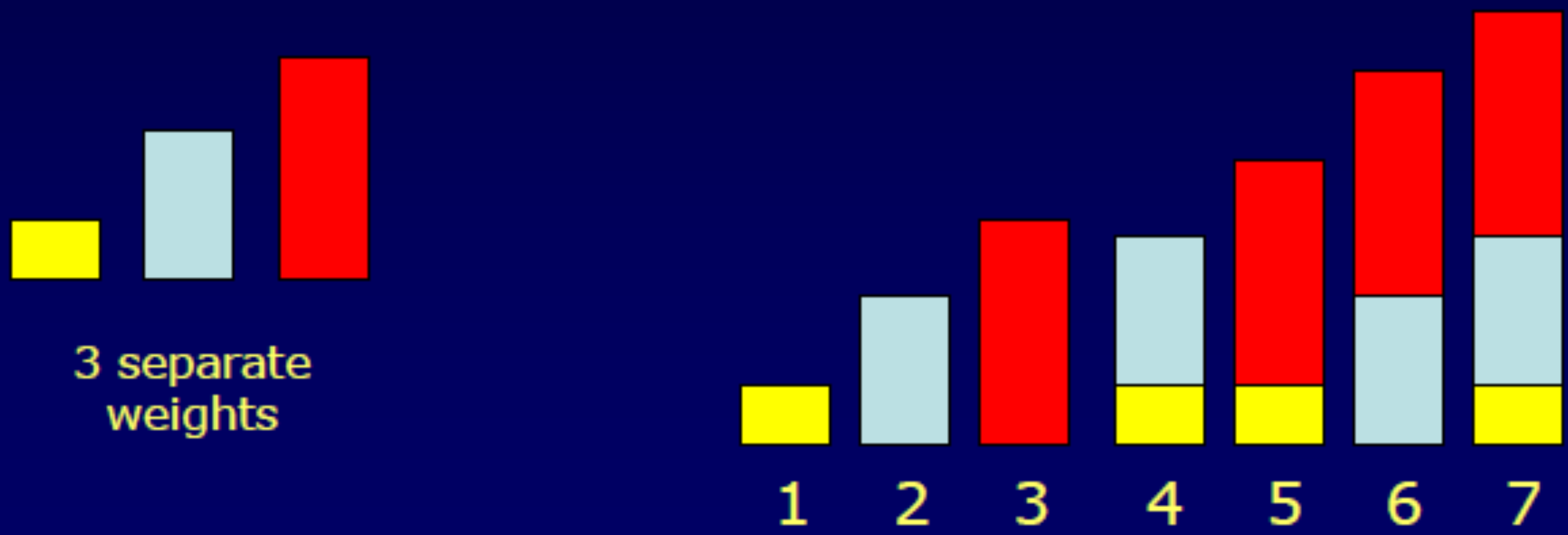
Add them up along with their weights...

Final intensity map from DAO



Small number of apertures can produce large number of intensity levels

Example: 3 apertures/angle



Small number of apertures can produce large number of intensity levels

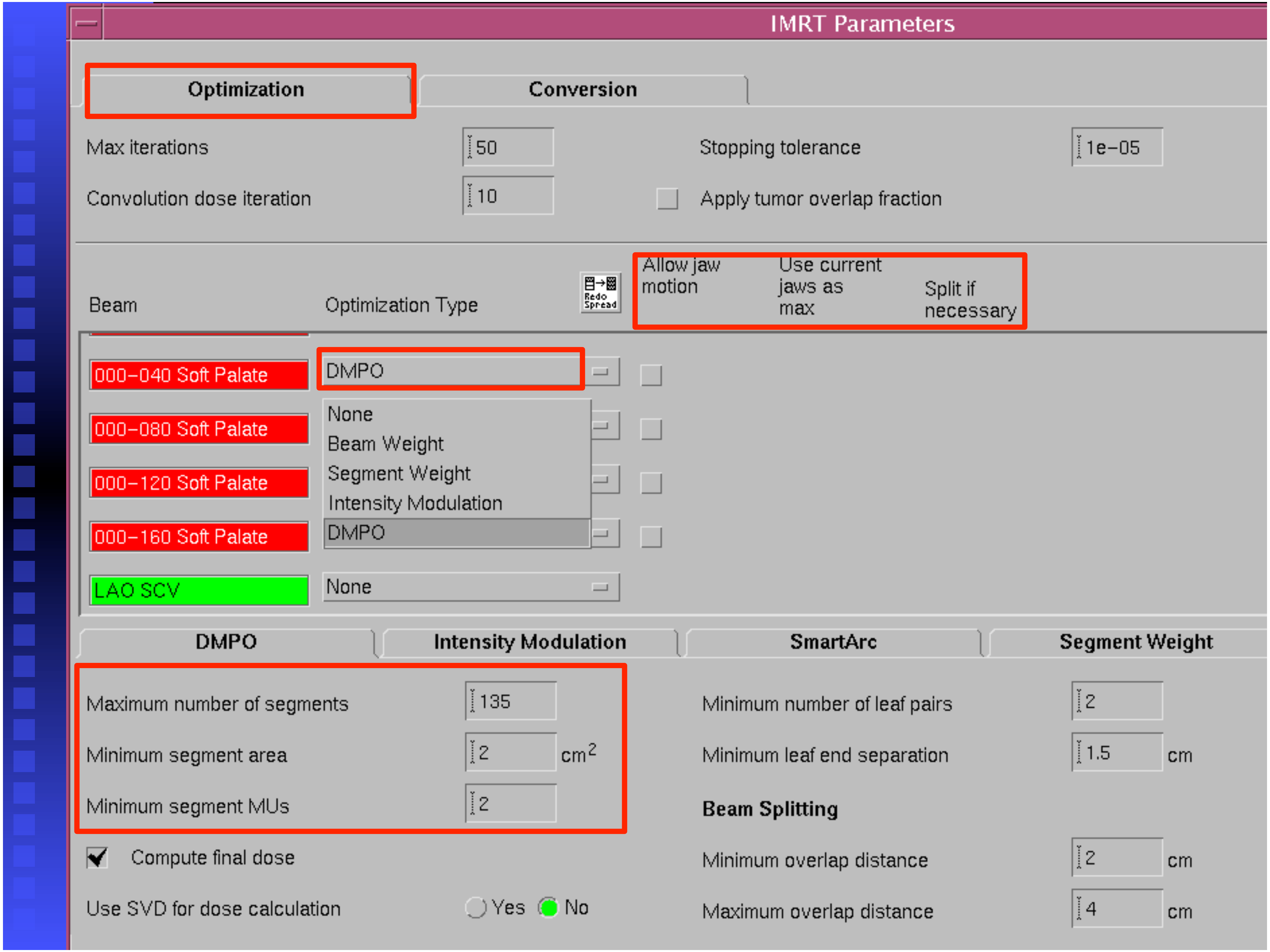
$$N_n = 2^n - 1$$

N = Number of intensity levels
n = Number of apertures

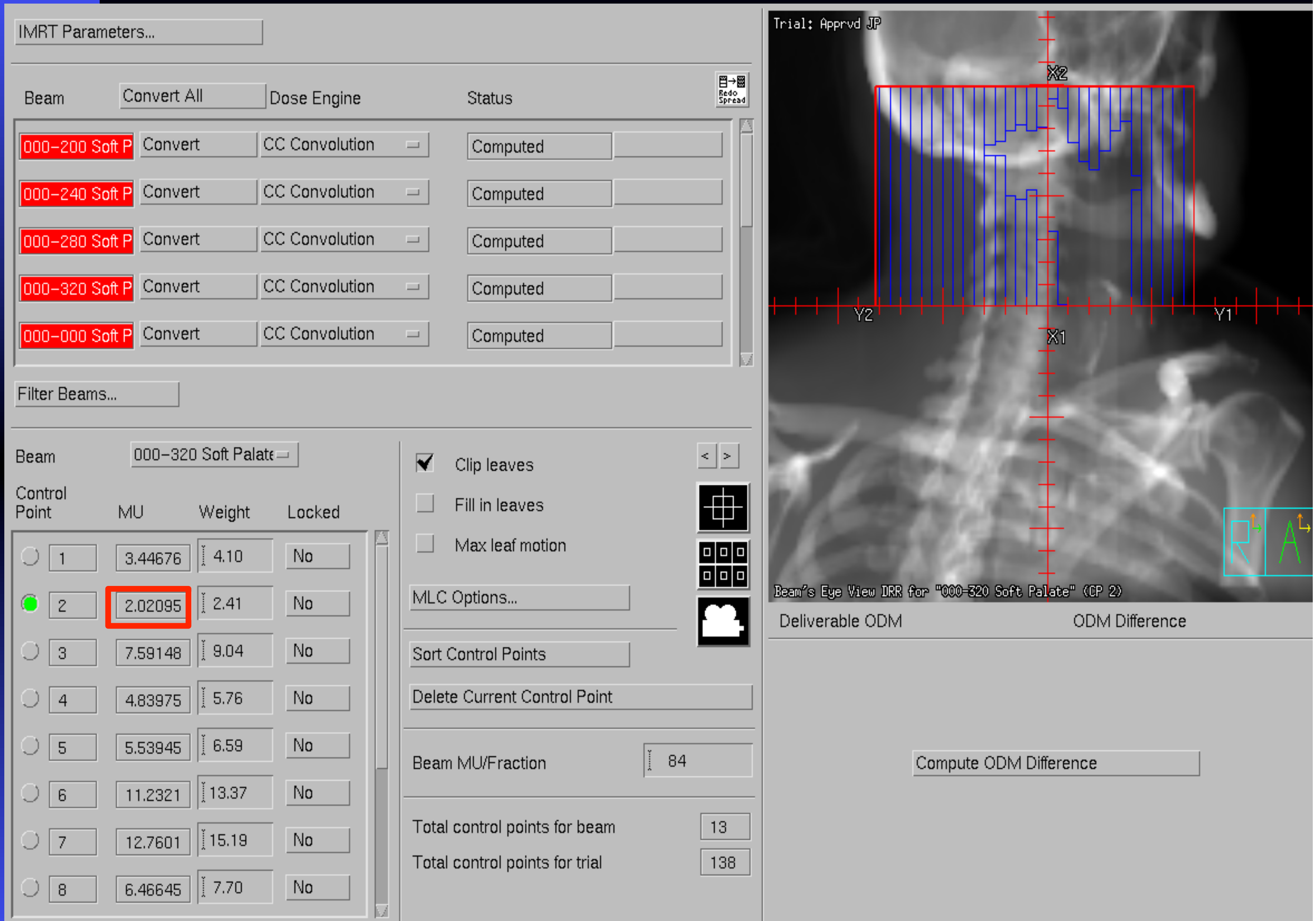
For 3 apertures, 7 intensities
For 4 apertures, 15 intensities
For 5 apertures, 31 intensities
For 6 apertures, 63 intensities

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.



IMRT Parameters
Optimization
Conversion
Max iterations
50
Stopping tolerance
1e−05
Convolution dose iteration
10
Apply tumor overlap fraction
Beam
Optimization Type
Redo Spread
Allow jaw motion
Use current jaws as max
Split if necessary
000−040 Soft Palate
DMPO
000−080 Soft Palate
000−120 Soft Palate
000−160 Soft Palate
None
Beam Weight
Segment Weight
Intensity Modulation
DMPO
LAO SCV
None
DMPO
Intensity Modulation
SmartArc
Segment Weight
Maximum number of segments
135
Minimum segment area
2
cm2
Minimum segment MUs
2
Minimum number of leaf pairs
2
Minimum leaf end separation
1.5
cm
Beam Splitting
Compute final dose
Minimum overlap distance
2
cm
Use SVD for dose calculation
Yes
No
Maximum overlap distance
4
cm


IMRT Parameters...
Beam
Convert All
Dose Engine
Status
Redo Spread
000–200 Soft P
000–240 Soft P
000–280 Soft P
000–320 Soft P
000–000 Soft P
Convert
CC Convolution
Computed
Filter Beams...
Beam
000–320 Soft Palate
Control Point
MU
Weight
Locked
1 3.44676 4.10 No
2 2.02095 2.41 No
3 7.59148 9.04 No
4 4.83975 5.76 No
5 5.53945 6.59 No
6 11.2321 13.37 No
7 12.7601 15.19 No
8 6.46645 7.70 No
Clip leaves
Fill in leaves
Max leaf motion
MLC Options...
Sort Control Points
Delete Current Control Point
Beam MU/Fraction 84
Total control points for beam 13
Total control points for trial 138
Trial: Apprvd JP
X2
Y2
Y1
X1
R
A
Beam's Eye View DRR for "000-320 Soft Palate" (CP 2)
Deliverable ODM
ODM Difference
Compute ODM Difference

Evaluating the Techniques

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

DMPO Summary

- Plan Quality
  - Total cost function ↓ 50% => Better normal tissue protection with more uniform dose to all target volumes
- Treatment delivery
  - Total MU ↓ 40% => Less Tx time
  - Segments ↓ 50% => Less down time

VMAT / IMAT

IMAT / VMAT Optimization

- IMAT treatment planning represents a particular complex optimization problem.
  - ✓ The size of the problem
  - ✓ Dynamic motion
  - ✓ Motion limitation
  - ✓ The dose calculation time

First Generation IMAT 2000-2007	Next Generation IMAT 2008-
• 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.	• 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

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

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.

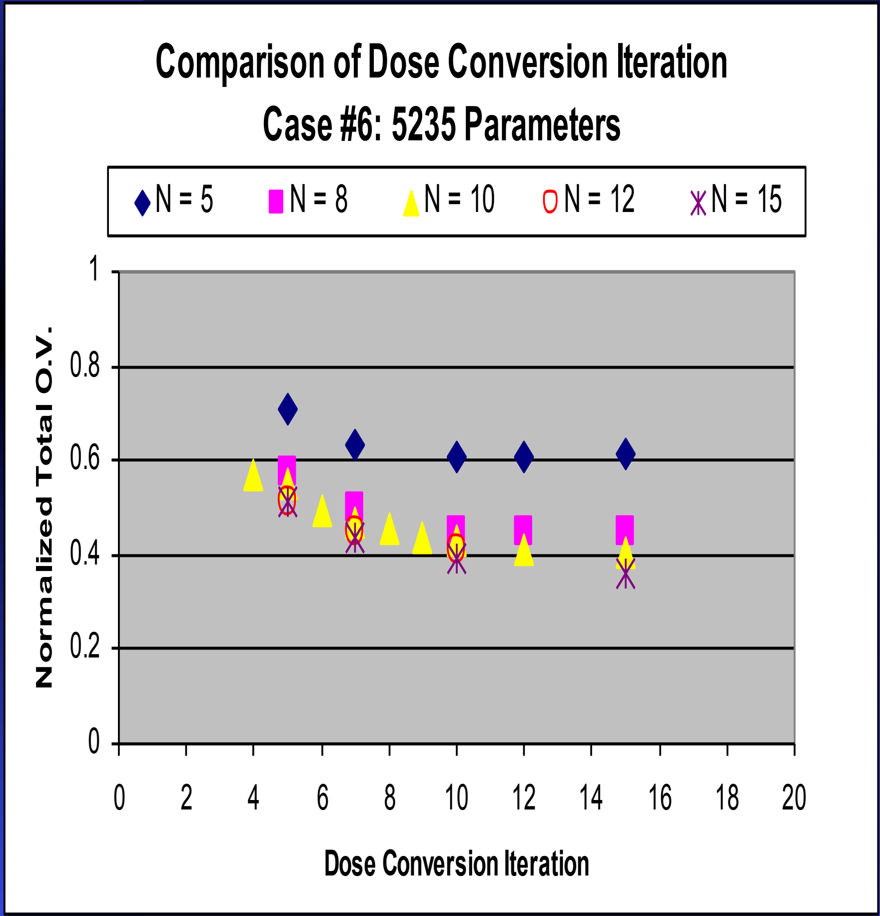
Courtesy of Philips Medical

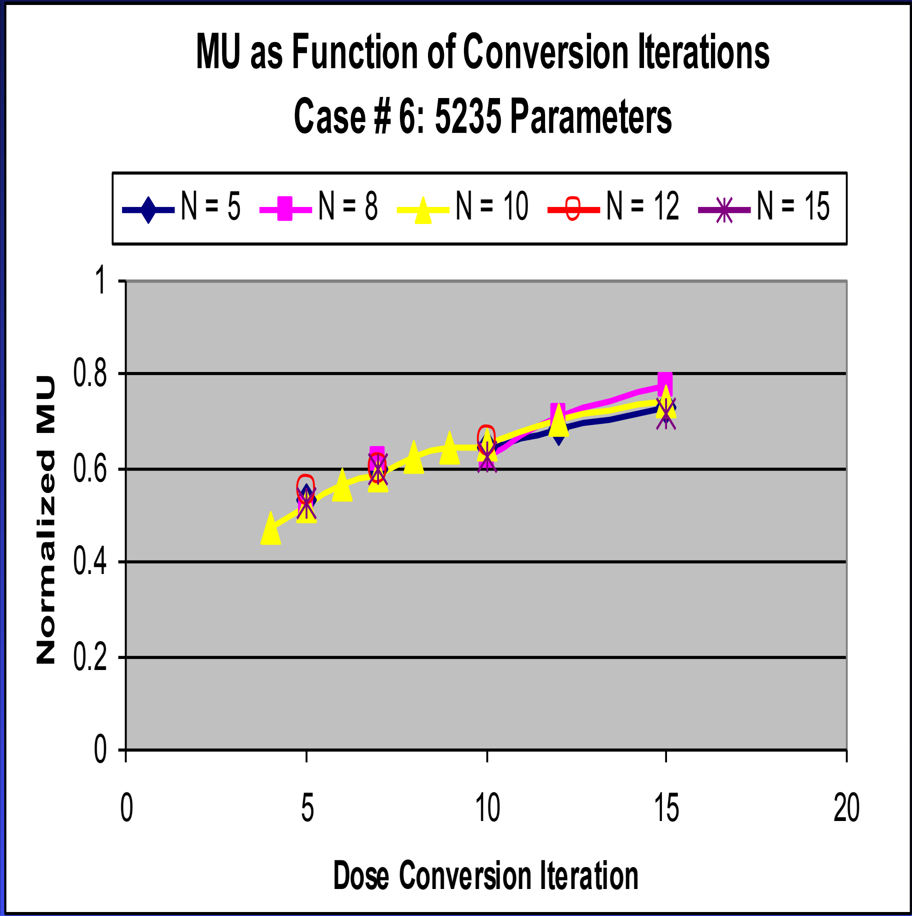
SmartArc Optimization (3)

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

N and n Optimization: An Intermediate Case





HN cases