Intensity Modulated Radiation Therapy: Delivery Types

ICPT School on Medical Physics for Radiation Therapy

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I hope you had a wonderful weekend!

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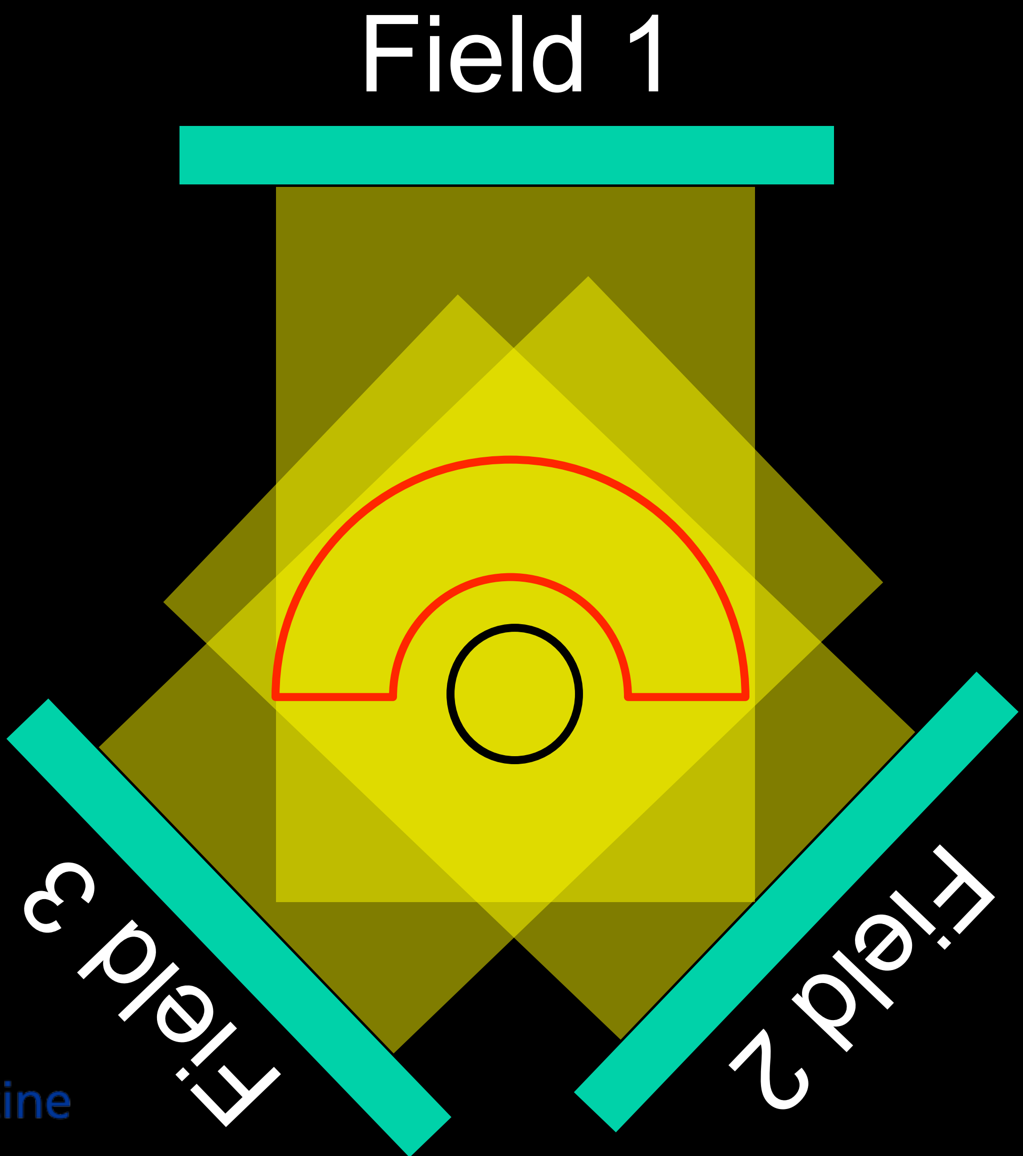
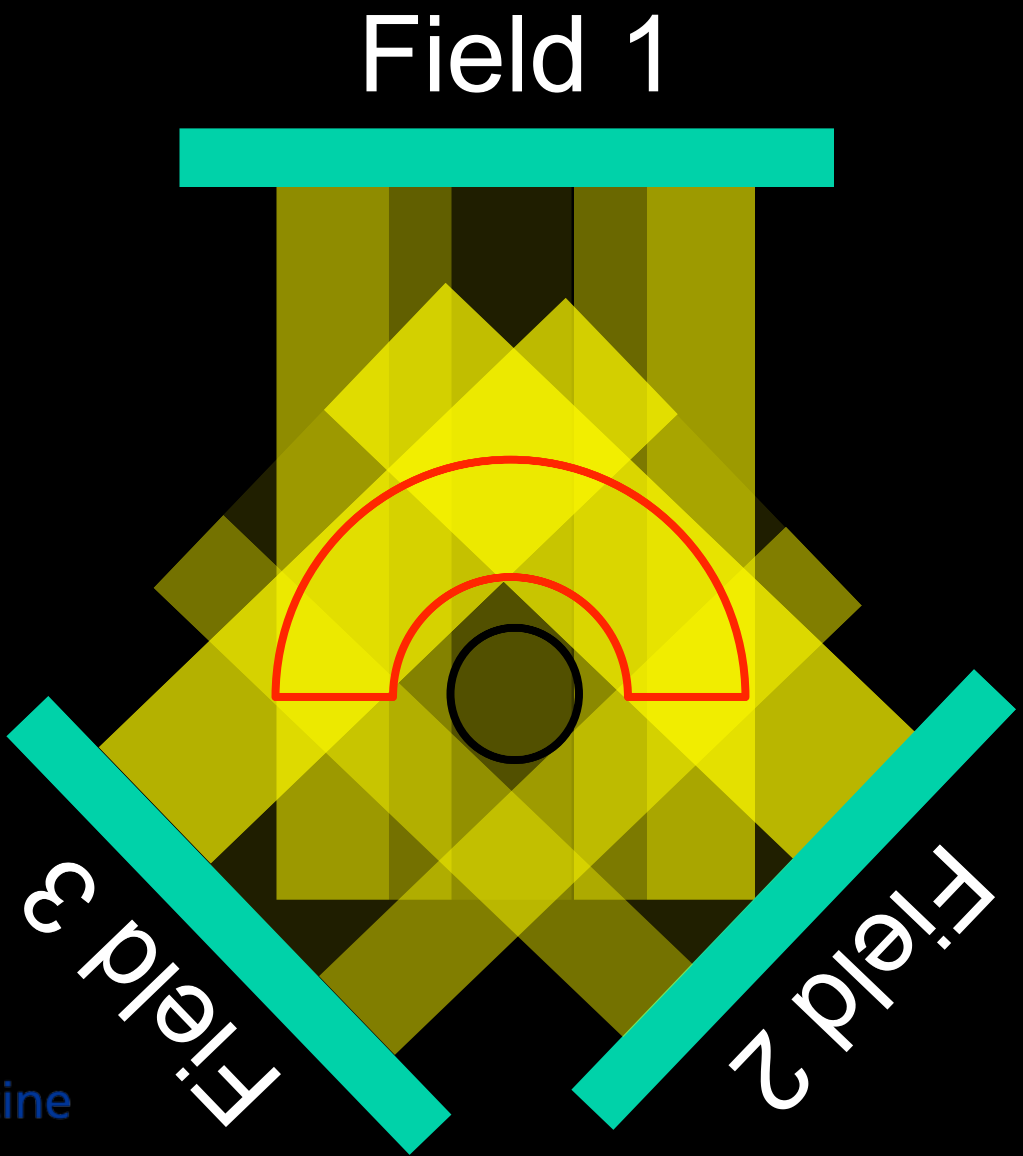
Topics

- IMRT Concept
- Compensators
- Step & Shoot (Static) IMRT
- Dynamic IMRT (sometimes called sliding window)

3D Radiation Therapy



IMRT Radiation Therapy



IMRT Radiation Therapy

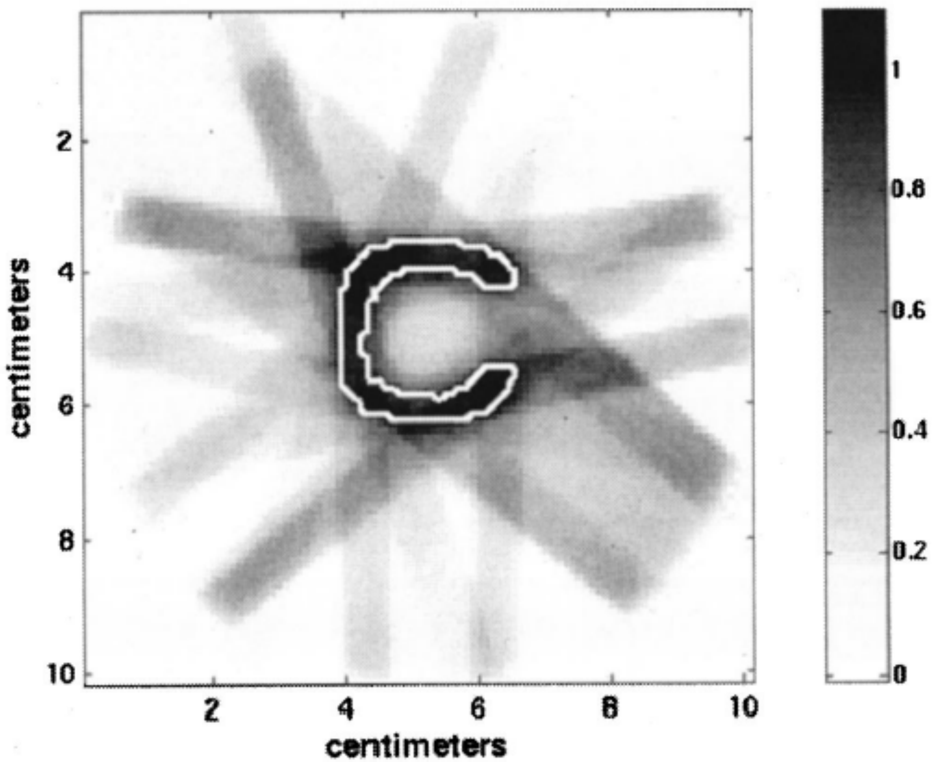


FIG. 9. An optimized dose distribution for a c-shaped target with a centrally located sensitive structure. In this case seven beams angles were used with seven apertures per beam direction. The target is outlined in white.

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Intensity Modulated Radiation Therapy (IMRT)

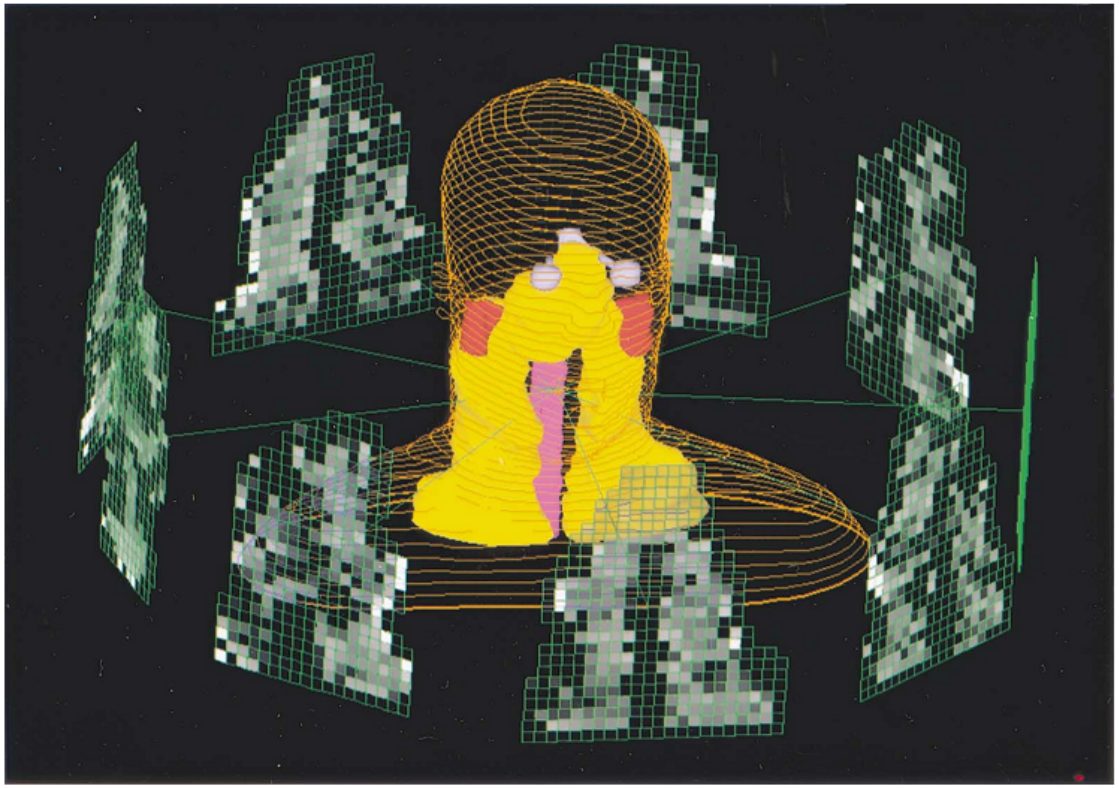

Fig. 1. Advanced form of 3D-CRT—IMRT—which is based on the use of optimized non-uniform radiation beam intensities incident on the patient. Shown is a 3D view of the patient, the PTV, spinal cord, and parotid glands, and the 9 intensity modulated beams (with gray levels reflecting the intensity value) used to generate the IMRT dose distribution.

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Forward Planning vs. Inverse Planning

Forward (conventional) Planning

- For all beams, the user defines:
  - geometry (gantry, collimator, couch settings)
  - collimation (jaw settings, MLC/block shape)
  - fluence (wedge vs open field, MU per beam)
  - IMRT can also be forward planned!
    - fluence defined manually

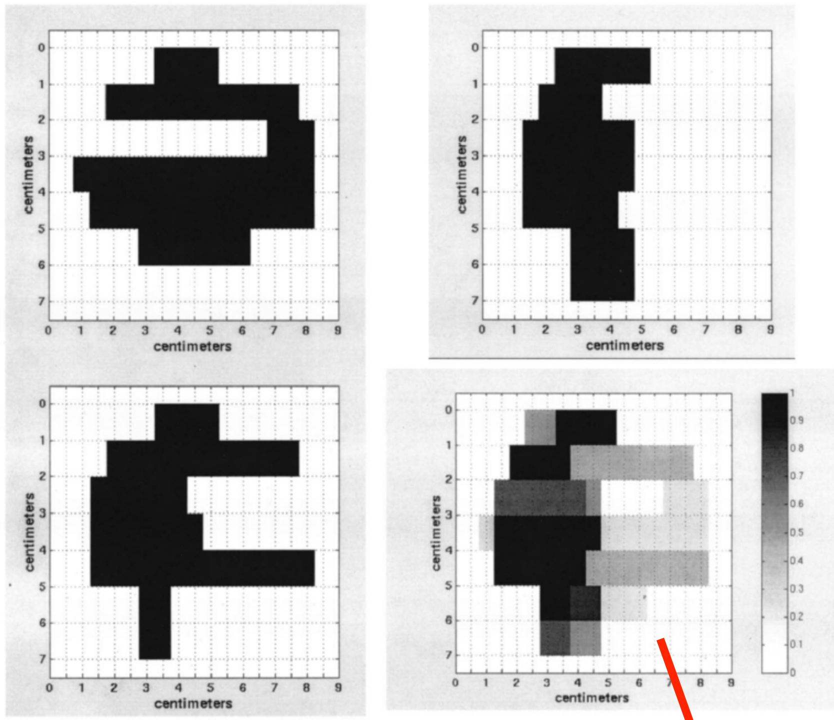
Inverse Planning

- User still (typically) defines:
  - geometry (gantry, collimator, couch settings)
- User defines dosimetric criteria & desired weighting for treatment plan
- Optimization algorithm defines collimation & beam fluence based on dosimetric criteria

Forward Planned IMRT

- Method 1: define fluence manually
  - fluence is defined by user
  - MLC leaf sequence is calculated to create the fluence
- Method 2: create multiple subfields (same beam geometry)
  - manually define MLC positions & relative weighting for each subfield

example of subfields



sum of subfields

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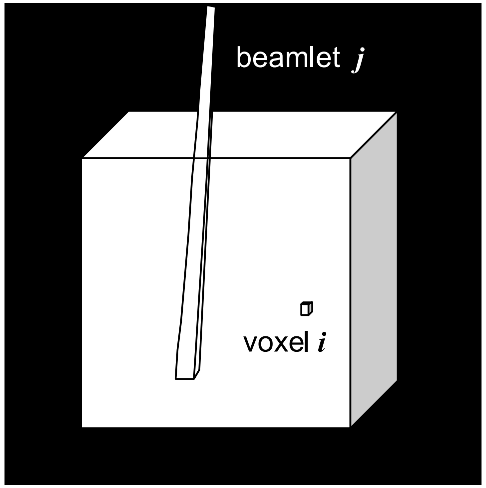
Inverse Planned IMRT: Optimization

- Beam fluence is divided into “beamlets”
- Beamlet dimensions:
  - 0.2-1.0cm along leaf motion direction
  - leaf width in cross-leaf direction
- Only optimize beamlets that traverse the target (plus small margin)

Inverse Planning: Optimization



- Dose in voxel *i* is given by

$$D_i = \sum_{j=1}^{J} a_{ij} w_j$$

where w_j is the intensity of the *j*th beamlet, i=1, …*I* is the number of dose voxels and where the sum is carried out from j = 1,..*J*, the total number of beamlets. We want to find w_j values

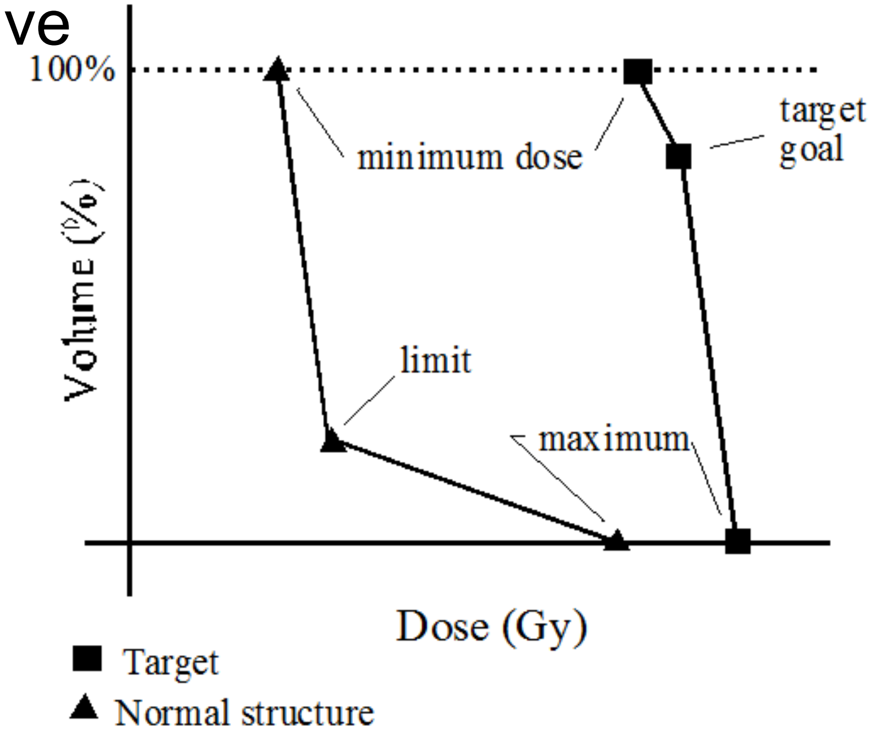
- The quantity a_{ij} is the dose deposited in the *i*th voxel by the *j*th beamlet for unit fluence

Inverse Planning: Optimization

- Dose in any voxel can be written as a linear combination of beamlet intensities.
- First step is to calculate the contribution to dose per unit fluence in each voxel due to each beamlet
- **Dose calculation is done "up front" rather than during optimization**
- (The same process is carried out regardless of dose calculation algorithm)

Inverse Planning: Optimization

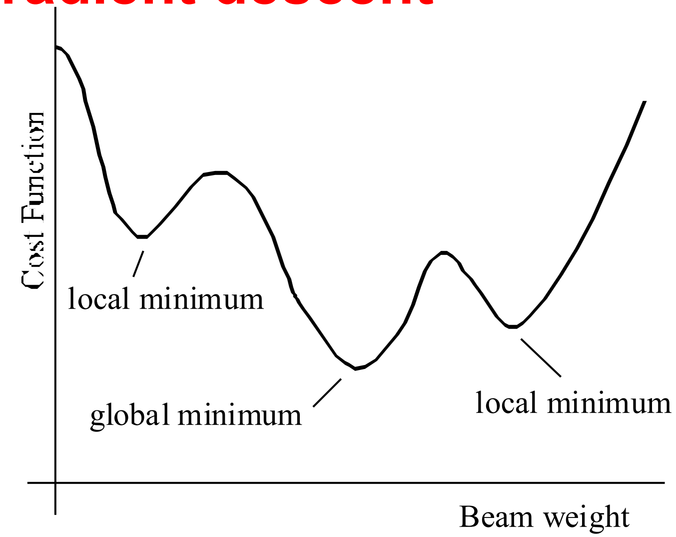
- Dose criteria typically defined using DVH
- Use cost function that quantifies how close the dose from the current beamlet weighting is to the objective



Optimization Algorithm

- Gradient descent
  - Always moves in direction of steepest descent
  - Fast, but can potentially get stuck in local minima
- Simulated Annealing
  - Stochastic: adds an element of randomness
  - Takes a random step & accepts it if cost function decreases
  - Random aspect decreases over time
  - Slower, but potentially more robust
- Others may also be used

most modern planning systems typically use a fast optimization algorithm such as gradient descent



exception: direct machine parameter optimization

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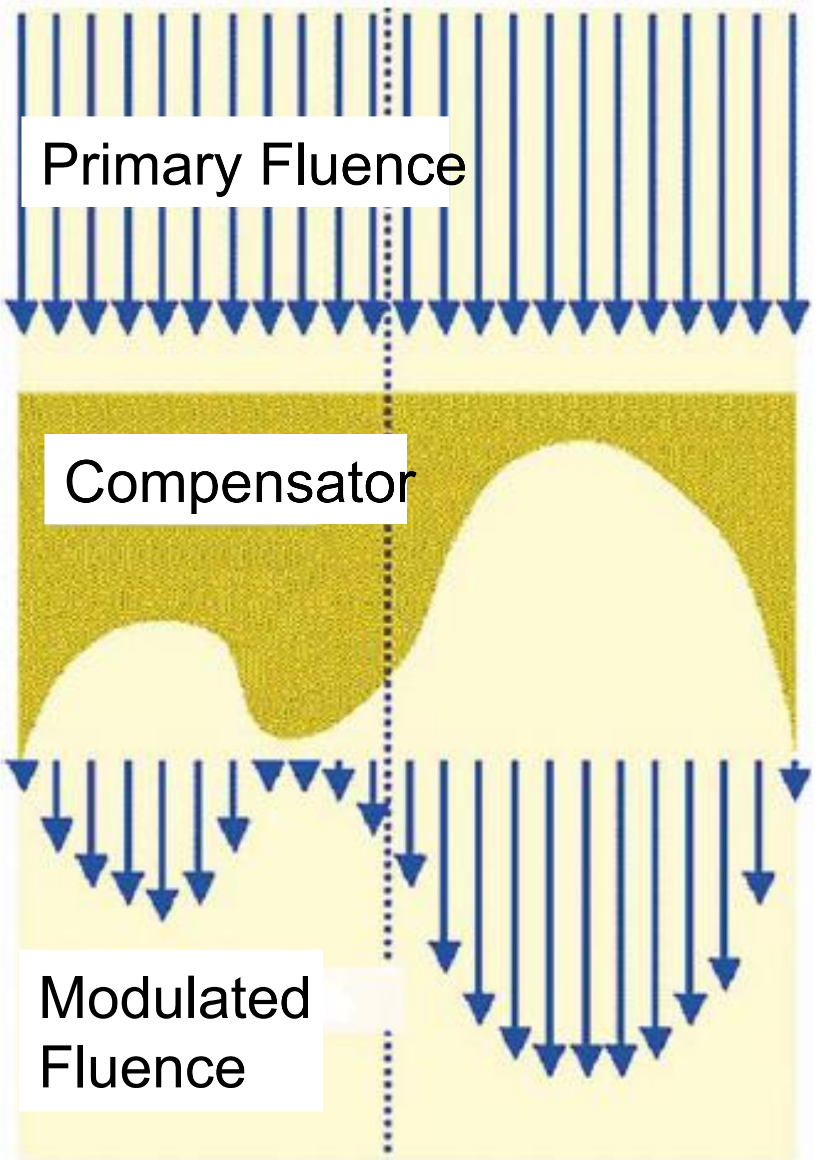
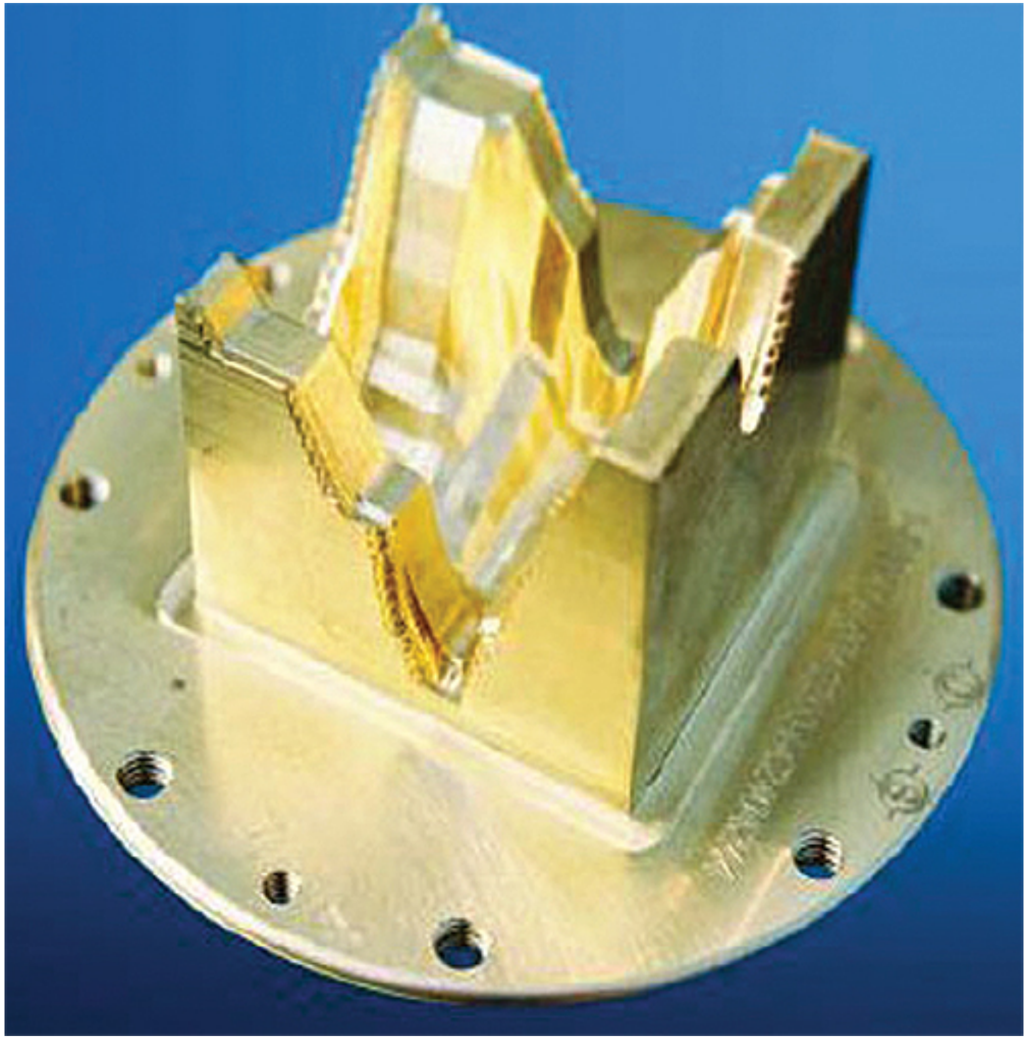
How to deliver the fluence?

- Physical Compensators
- MLC motion
  - leaf sequence to match ideal fluence
  - Direct Machine Parameter Optimization (Direct Aperture Optimization)
    - skip fluence step! Or in other words: the leaf sequence is optimized and comes first; the fluence can be calculated from the leaf sequence.

IMRT Methods: Physical Compensator





IMRT Methods: Physical Compensators

reusable tin granules & compensator box

disposable styrofoam mold

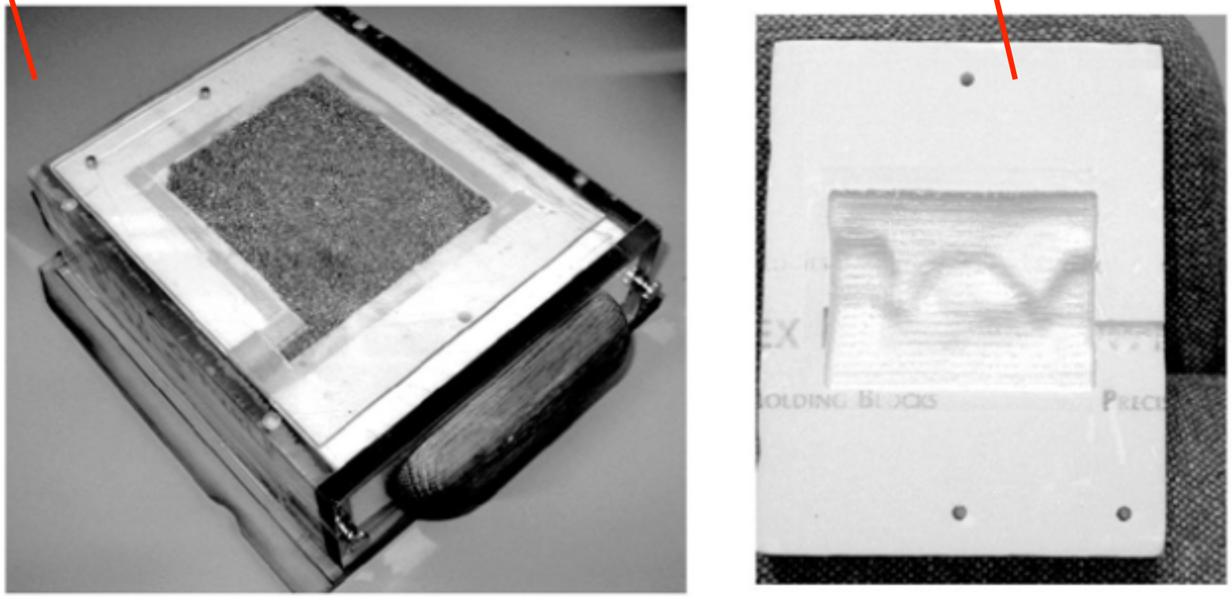


FIG 4. Compensator box with a tin granule-filled compensator enclosed (left) and a Styrofoam compensator mold (right). The three reference holes on the mold and the matching set on the box are used for easy verification of the compensator orientation in the box. The compensator is designed to be inserted in the wedge slot of an accelerator.

IMRT Methods: Physics Compensators

Advantage: simple implementation

- no need for MLCs
- static delivery
- no interplay between intensity modulation and organ motion

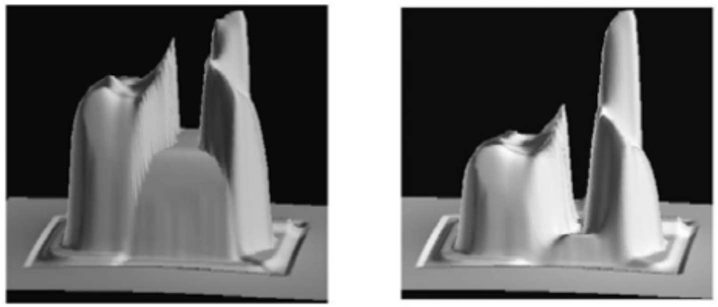
Disadvantage: lack of automation

- each field requires a custom compensator
- need to enter room per field
- Limited modulation

IMRT Methods: Physical Compensators

- Max compensator thickness ~5cm
- tin:
  - 100% - 38% 6X
  - 100% - 45% 15X
- tungsten powder:
  - 100% - 18% 6X
  - 100% - 20% 15X

actual fluence vs ideal fluence



IMRT Methods: Physical Compensators

Ideal Compensator Criteria:

- large range of intensity modulation magnitude
- intensity modulation of high spatial resolution
- not hazardous during fabrication
- easy to form to & retain shape
- low material cost
- environmentally friendly

Material	Pro	Con
Cerrobend (with and without mold)	• readily available • inexpensive • recyclable • high density	• need a milling machine
brass/steel/ lead (cube or sheet)	• no milling required • recyclable • inexpensive	• poor IM resolution due to discreteness • can be labor-intensive for assembly. • can be hazardous (lead)
Lucite (solid)	• easy to machine • nonhazardous	• low density thus low IM magnitude • need a milling machine • not recyclable thus can be expensive
brass/steel (solid)	• readily available • can produce smooth IM • nonhazardous	• not recyclable thus can be expensive • need a milling machine
tin granule-wax (mixture in mold)	• recyclable • can produce smooth IM • nonhazardous	• low density thus low IM magnitude • need a milling machine • difficult to keep consistent packing density
tin/steel (granule in mold)	• high IM resolution • consistent packing • nonhazardous • recyclable	• medium density -medium IM magnitude • need a milling machine
tungsten (powder in mold)	• high IM resolution • consistent packing • high density • recyclable	• slightly hazardous to handle in coarse powder form (less than Cerrobend and lead) • need a milling machine

Table 2. Pros and cons of selected materials for the IMRT compensator application

MLC Based IMRT:

- Leaf Sequencing Algorithm:
  - "Inverse optimization" derives "fluence" per field
  - "Leaf sequencing algorithm" determines an MLC motion to deliver the fluence
  - There will likely be some difference between the "optimal" and "actual" fluence
- Alternative Strategy: Direct Machine Parameter Optimization (DMPO) or Direct Aperture Optimization (DAO)
  - Actual machine parameters (leaf positions, etc.) optimized directly
  - Advantage: what you see (at optimization) is what you get
  - Disadvantage: potentially slower optimization

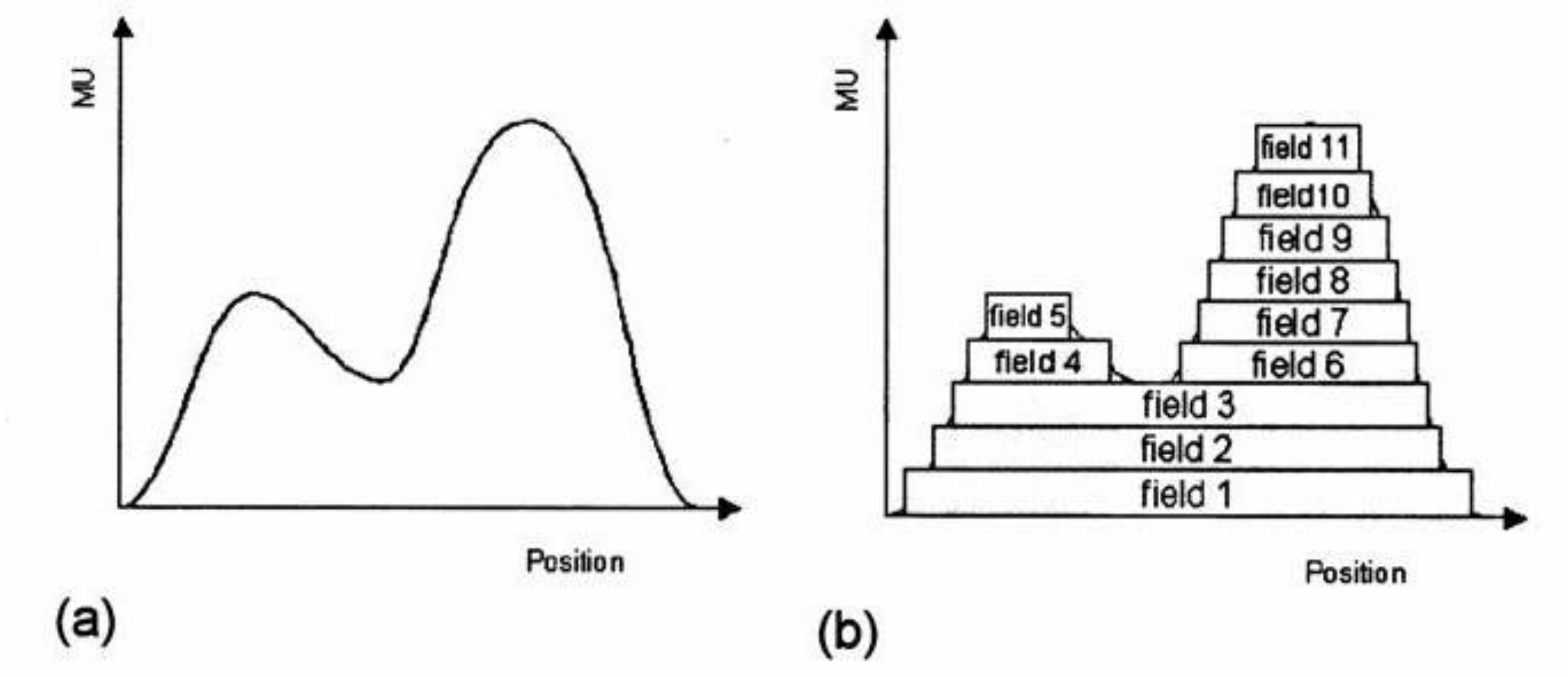
Leaf Sequencing Algorithm:

- There are many solutions to create a desired fluence
  - some idealized intensity patterns may not be deliverable
  - leaf transmission sets a lower bound on intensity
- Must account for limitations in leaf position & leaf speed
- Algorithms may attempt to minimize:
  - # segments
  - MU
  - leaf travel or delivery time
  - tongue & groove effect
- The difference between actual & desired intensity may be greater for complicated intensities; these also lead to more complicated leaf sequences, increased MU, and / or # segments
  - because of this often the inverse optimization may smooth the fluence or include a penalty for complex fluences

Leaf Sequencing Algorithm:

- The final dose calculation from the treatment planning system may be based on either the ideal fluence OR the final fluence from the leaf sequence
  - important to know which is being reported, since a dose degradation may be expected between these two
  - greater degradation may be expected for more complicated fluence patterns
- Dose calculation during optimization may be simplified to increase speed

IMRT Methods: Step & Shoot (static MLC)



IMRT leaf sequencing

leaves may “close in” with each segment

or “sweep across” the field (this is the method always used for dynamic MLC IMRT)

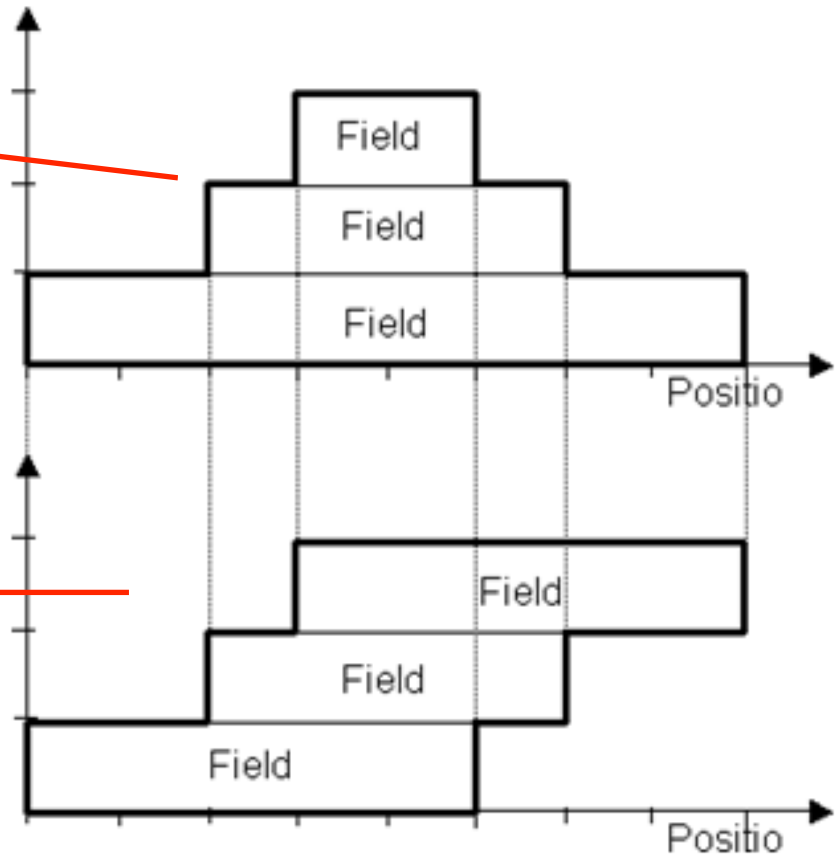
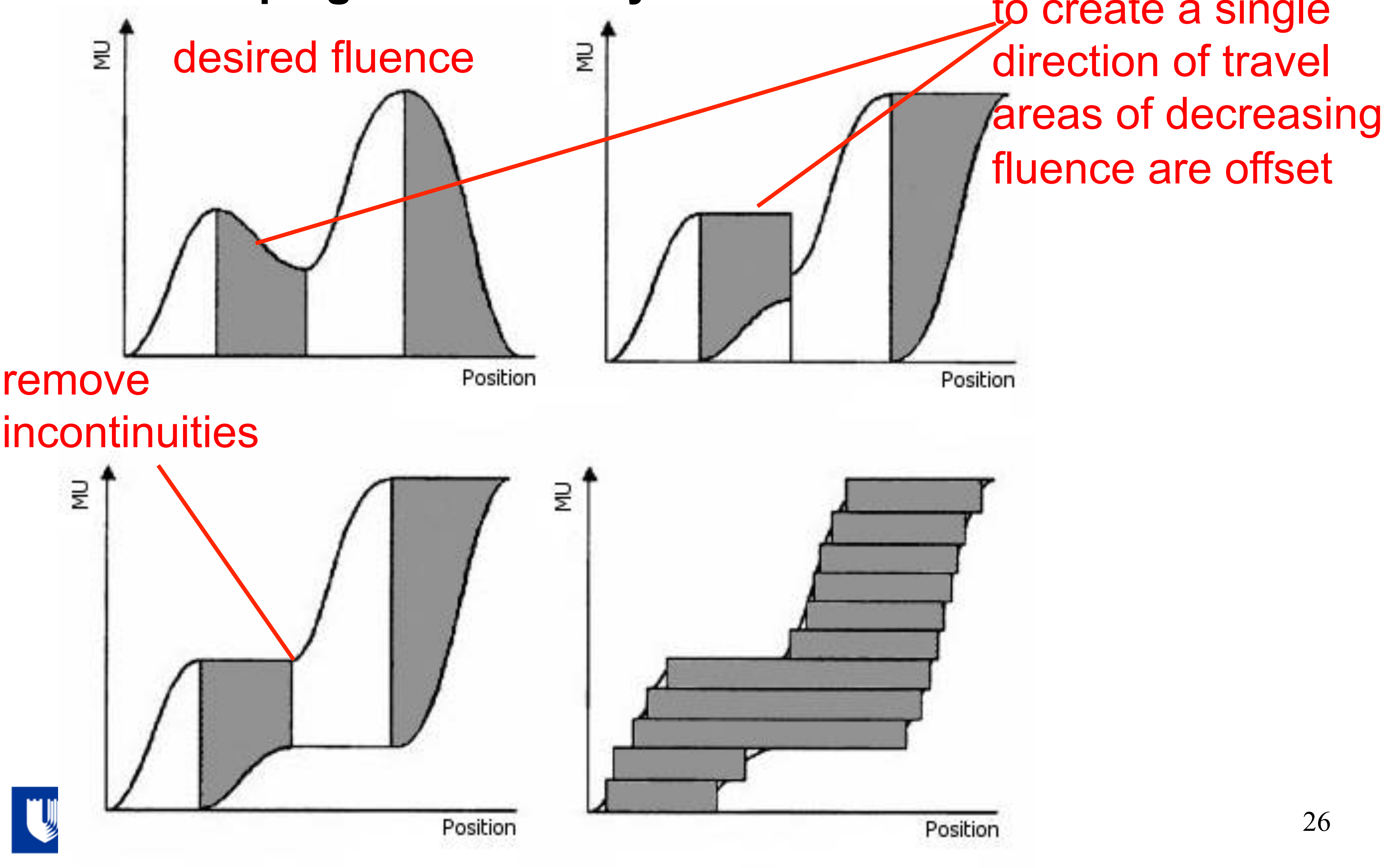


Figure 10.11: The close-in decomposition and the leaf-sweep decomposition illustrated using a simple pyramidal intensity profile

same fluence can be delivered with both methods

IMRT Methods:
Sweeping Leaves for dynamic MLC



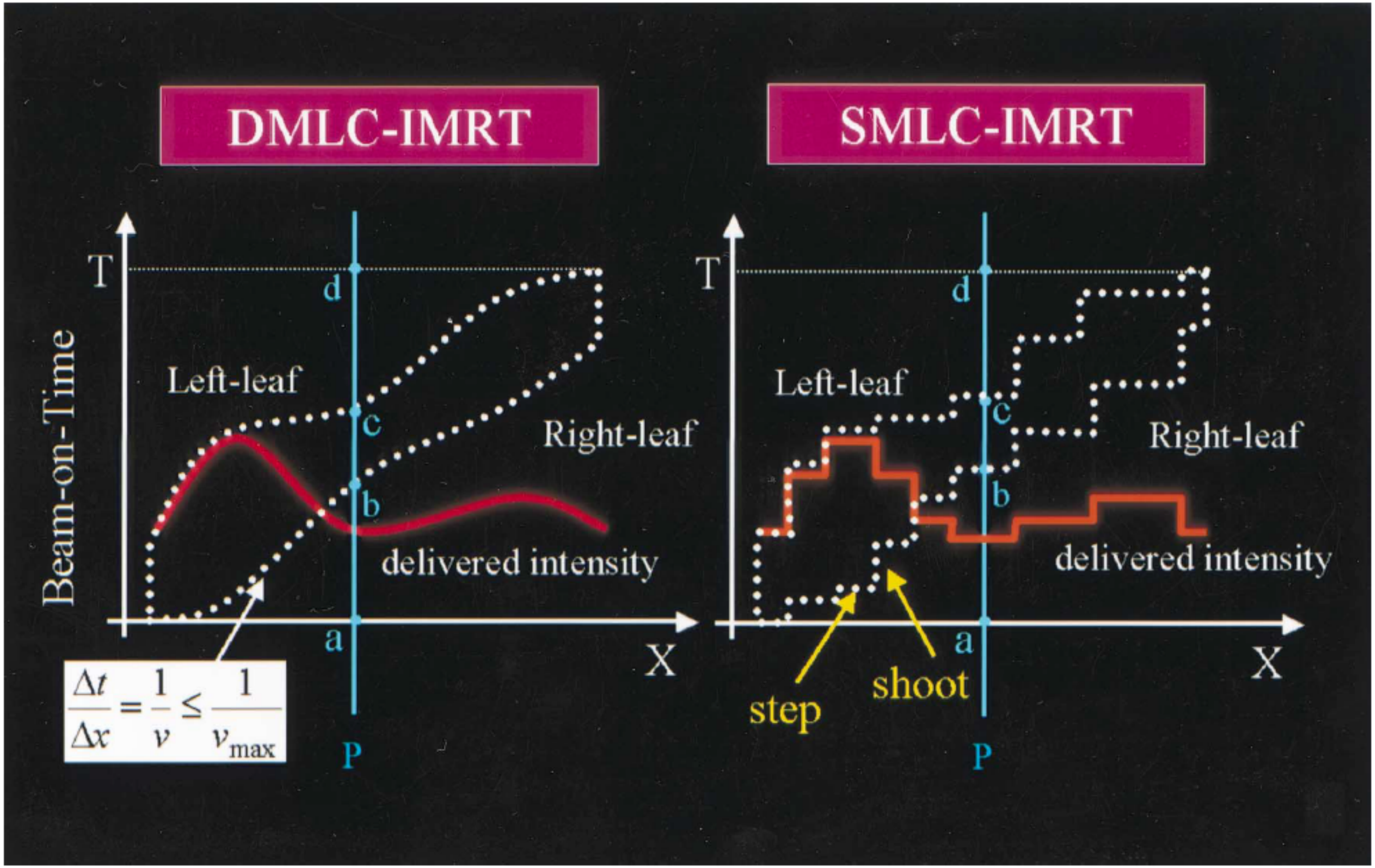


Fig. 6. (A) Intensity profile delivered by the leaves' paths of Fig. 5 (replotted here as dotted lines). In practice, a "leaf-sequencing" algorithm is used to translate the desired intensity profiles into a computer data file of the leaf positions as a function of MUs. (B) SMLC technique of delivering IMRT (also referred to as the *step-and-shoot* method). In the "step" phase, the leaves travel to discrete positions, then the radiation beam turns on in the "shoot" phase (i.e., alternate MLC movement and radiation delivery). The result is discrete intensity levels, the number of which depends on the "step" number.

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Direct Machine Parameter Optimization

- user specifies beam geometry & number of segments
- leaf positions (per segment) initially set to beams eye view
- optimization to meet dose criteria using simulated anealing
- can disallow invalid MLC positions, MLC motion constraints, & very low MU segments

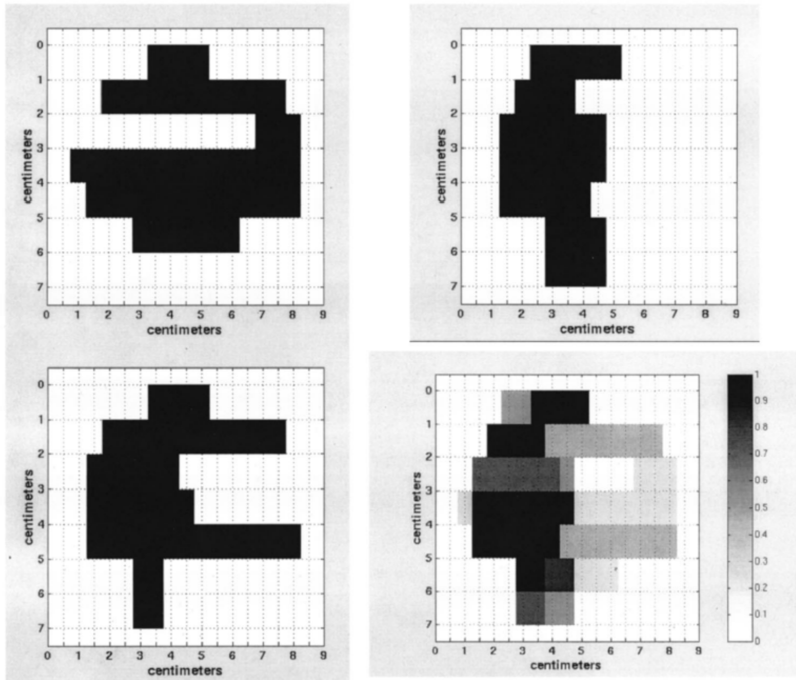

FIG. 7. The three aperture shapes and corresponding intensity map for one beam direction. The open area of each aperture is shown in black.

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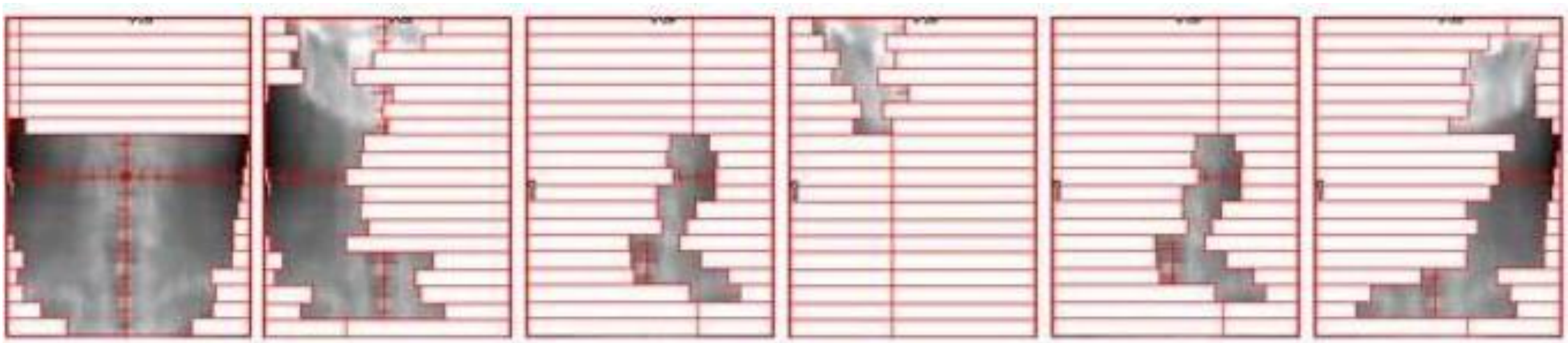
IMRT Methods: Step & Shoot (static MLC)

fluence from sum of all subfields (or segments)

Segments (subfields) may be defined by *forward* planning, or *inverse* planning. Segments from inverse plans may be derived via a leaf sequence algorithm, or directly from optimization (DMPO)!



IMRT 'step and shoot' and sliding window

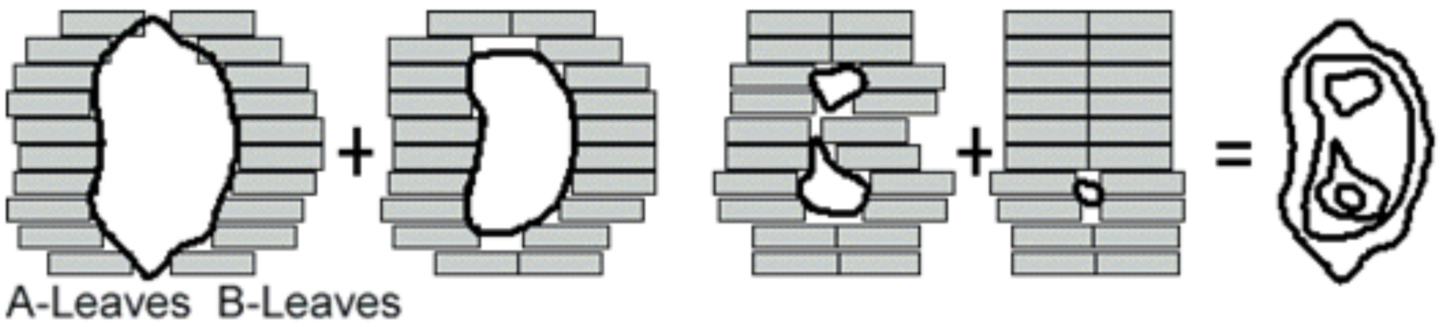


Figure 10.8: The basic idea of the step and shoot approach is to deliver an intensity modulated beam as a superposition of a set of irregularly shaped, partially overlapping field components

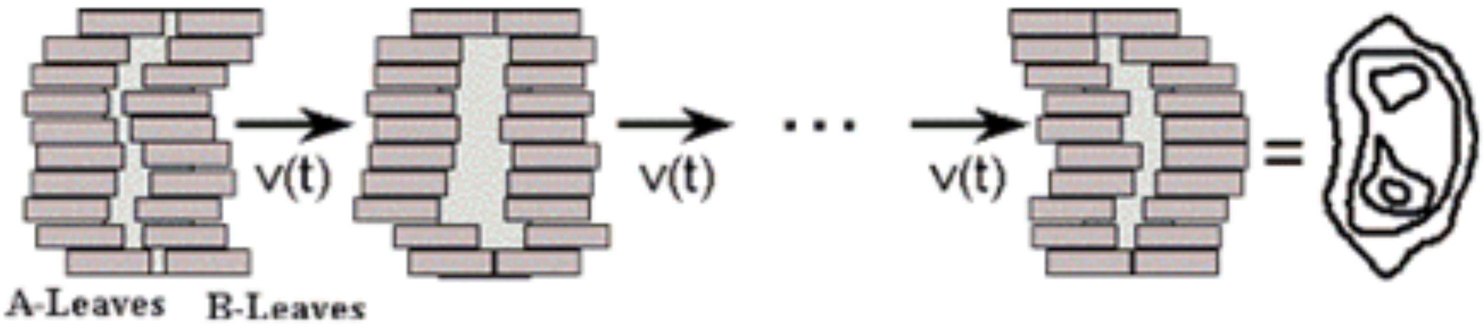
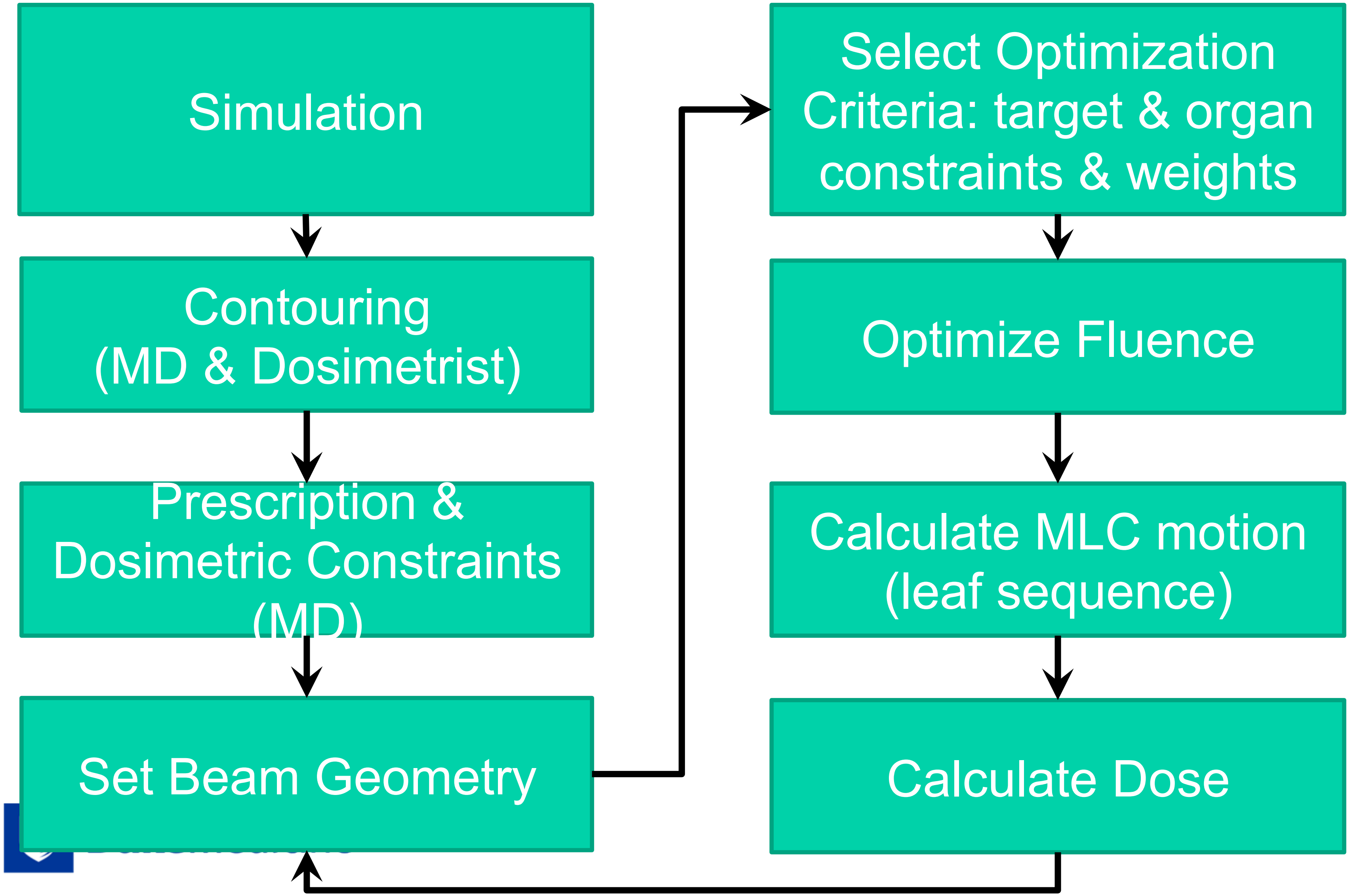


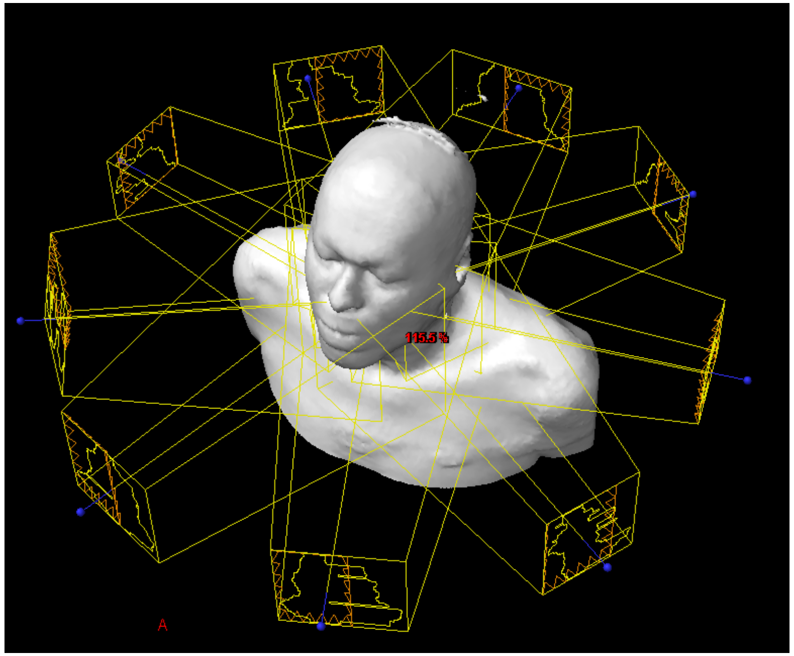
Figure 10.9: Principle of dynamic multi leaf collimation

IMRT Treatment Planning Process



IMRT: Beam Setup

- Typically 7-12 equi-spaced beams
- Isocenter placed near center of PTV



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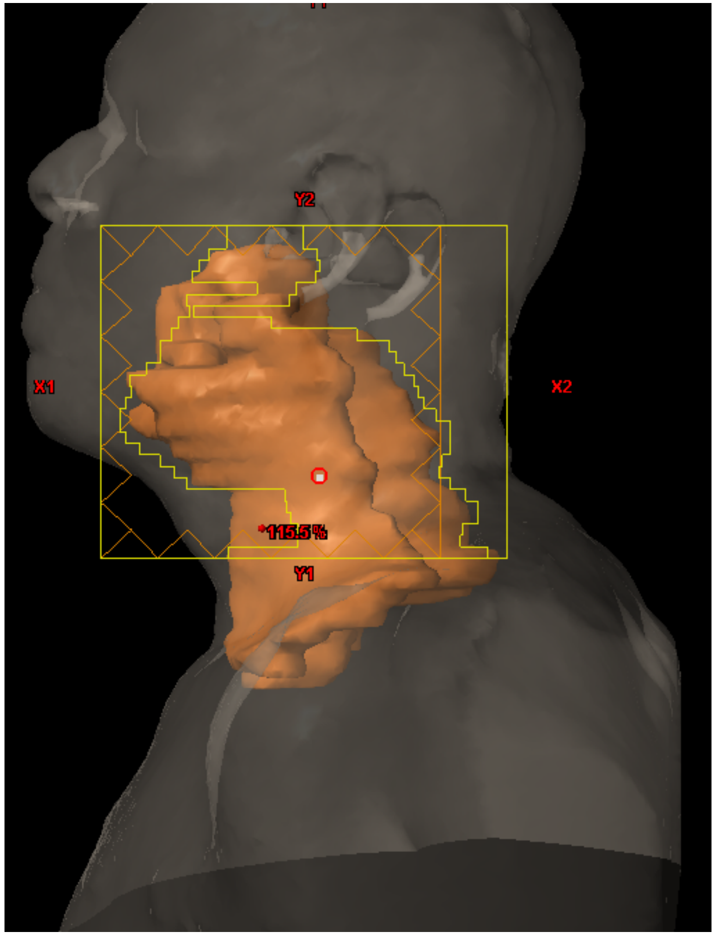
IMRT Beam Setup

- Lateral beams: still avoid going through shoulders



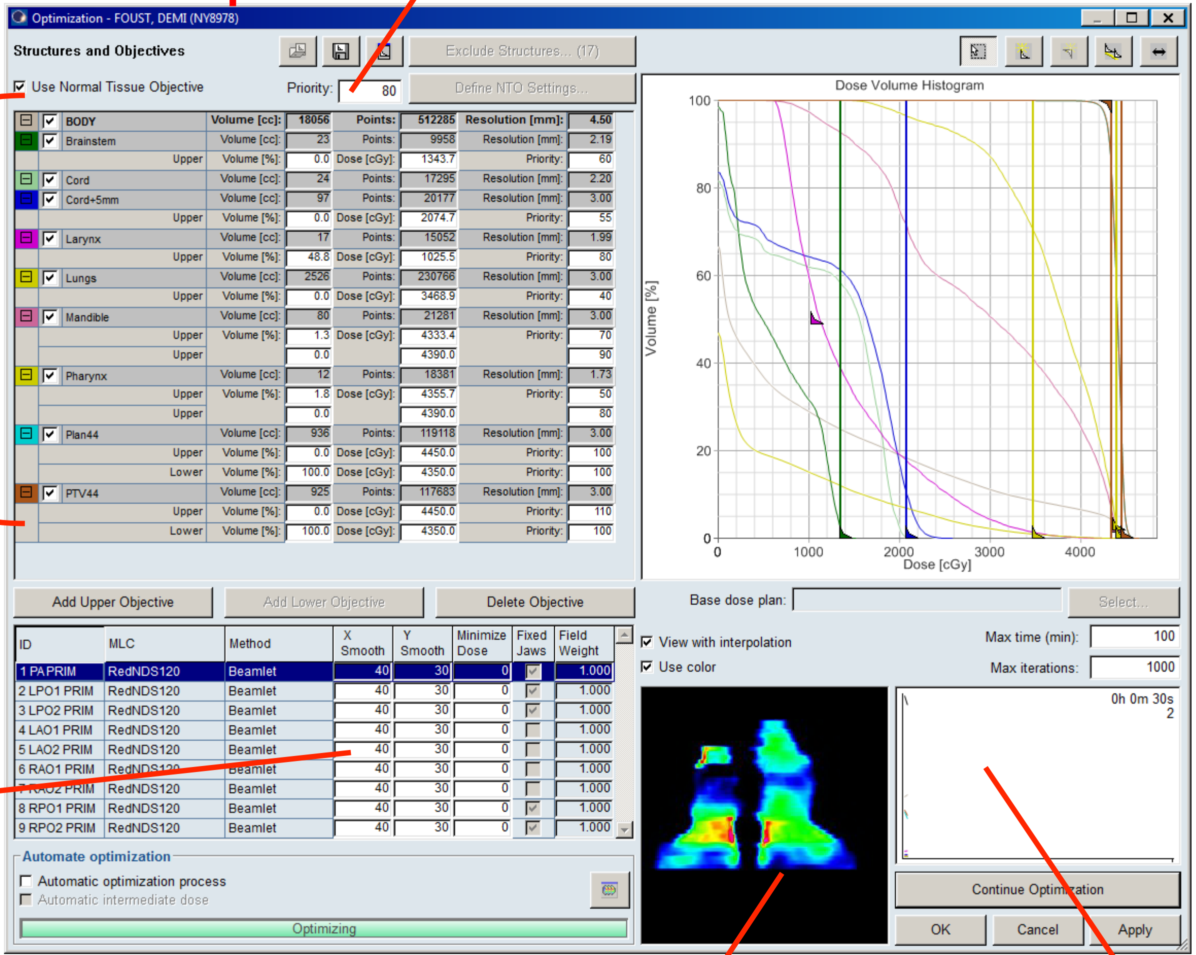
Inverse Planning: Optimization (Eclipse)

normal tissue optimization constraint

dosimetric criteria

& dose volume historgram

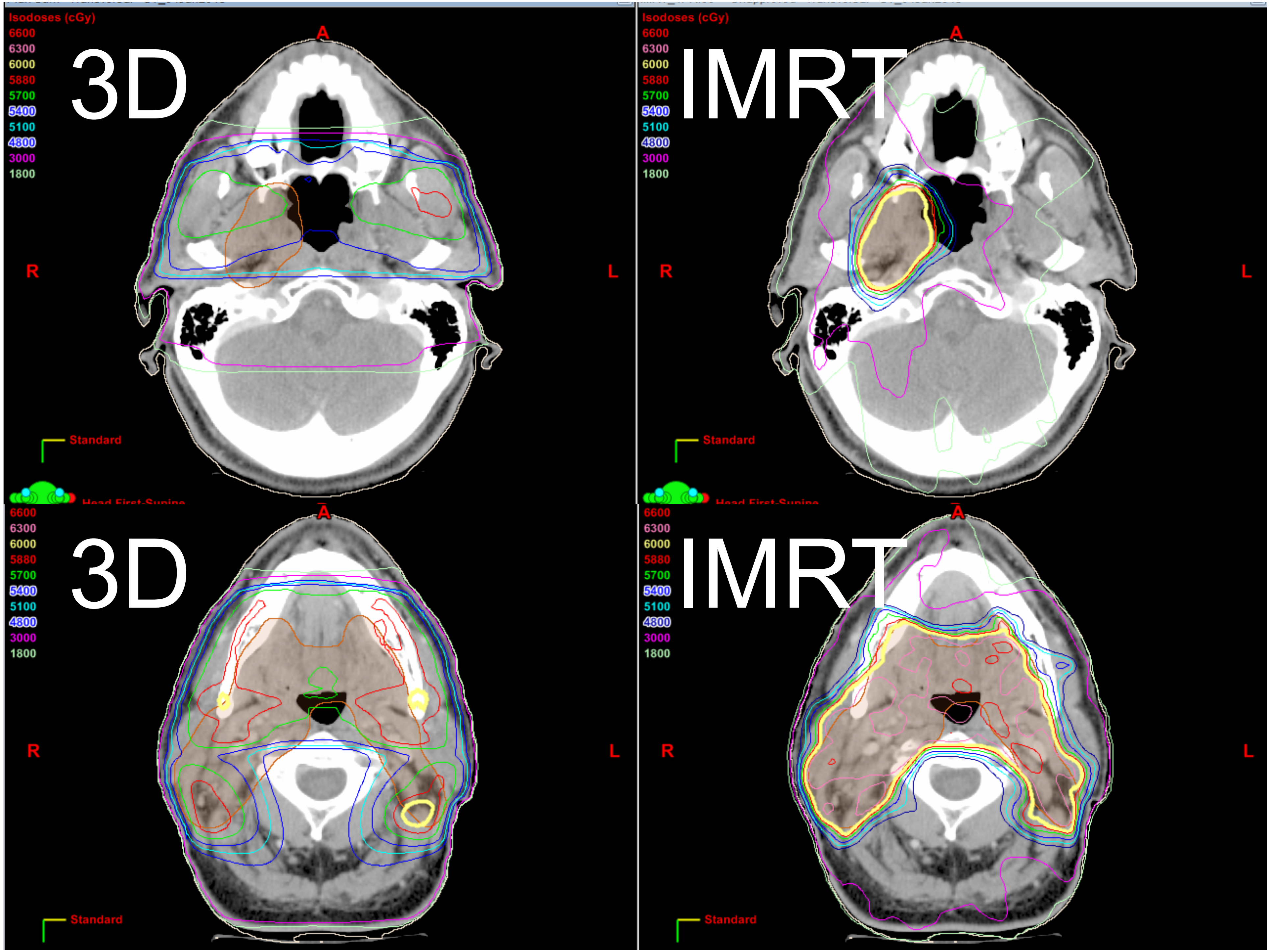
dosimetric criteria



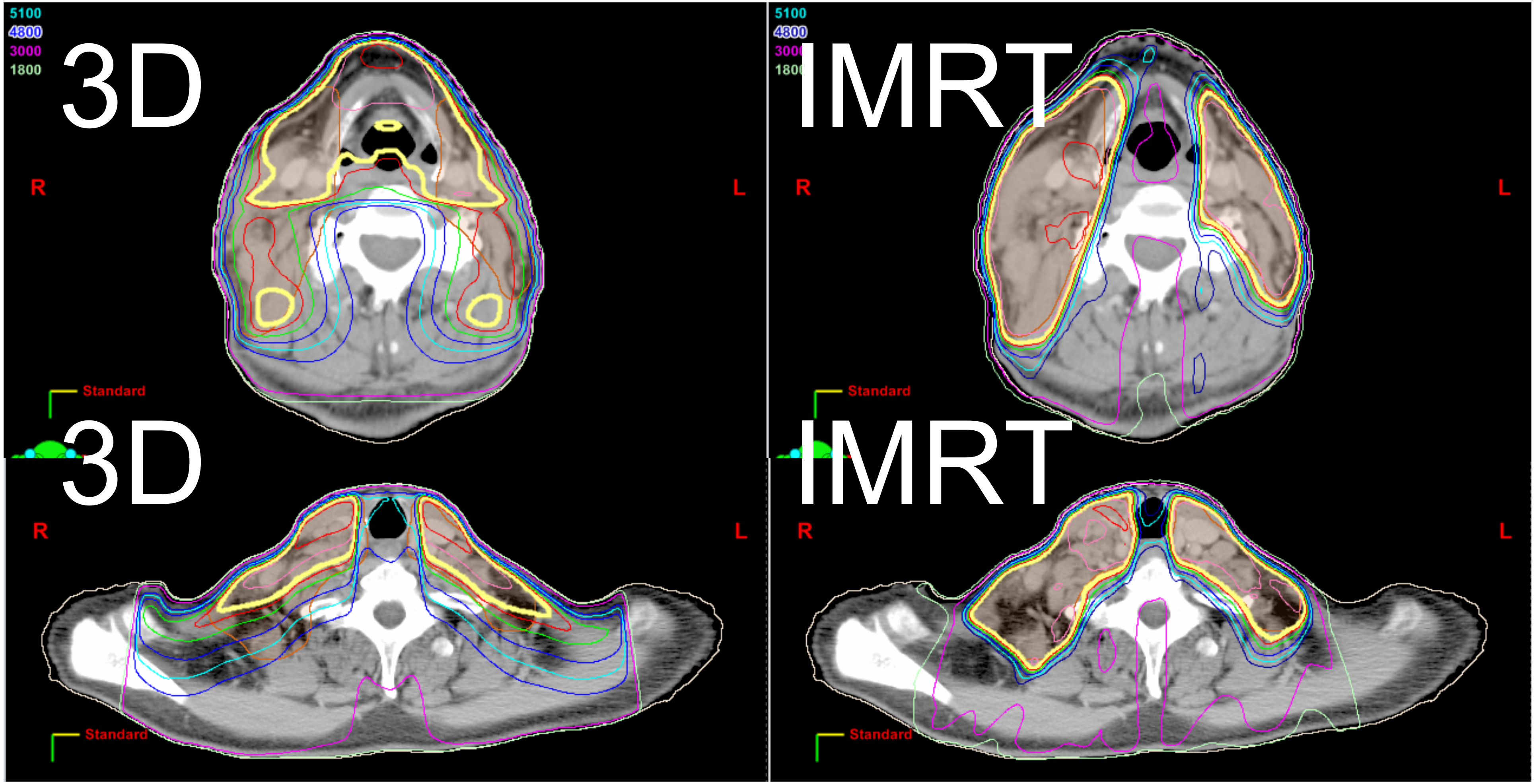
penalty to smooth fluence

beam fluence

objective function


Isodoses (cGy)
6600
6300
6000
5880
5700
5400
5100
4800
3000
1800
3D
IMRT
A
R
L
Standard
Head First-Supine

3D vs IMRT


5100
4800
3000
1800
3D
R
L
Standard
3D
R
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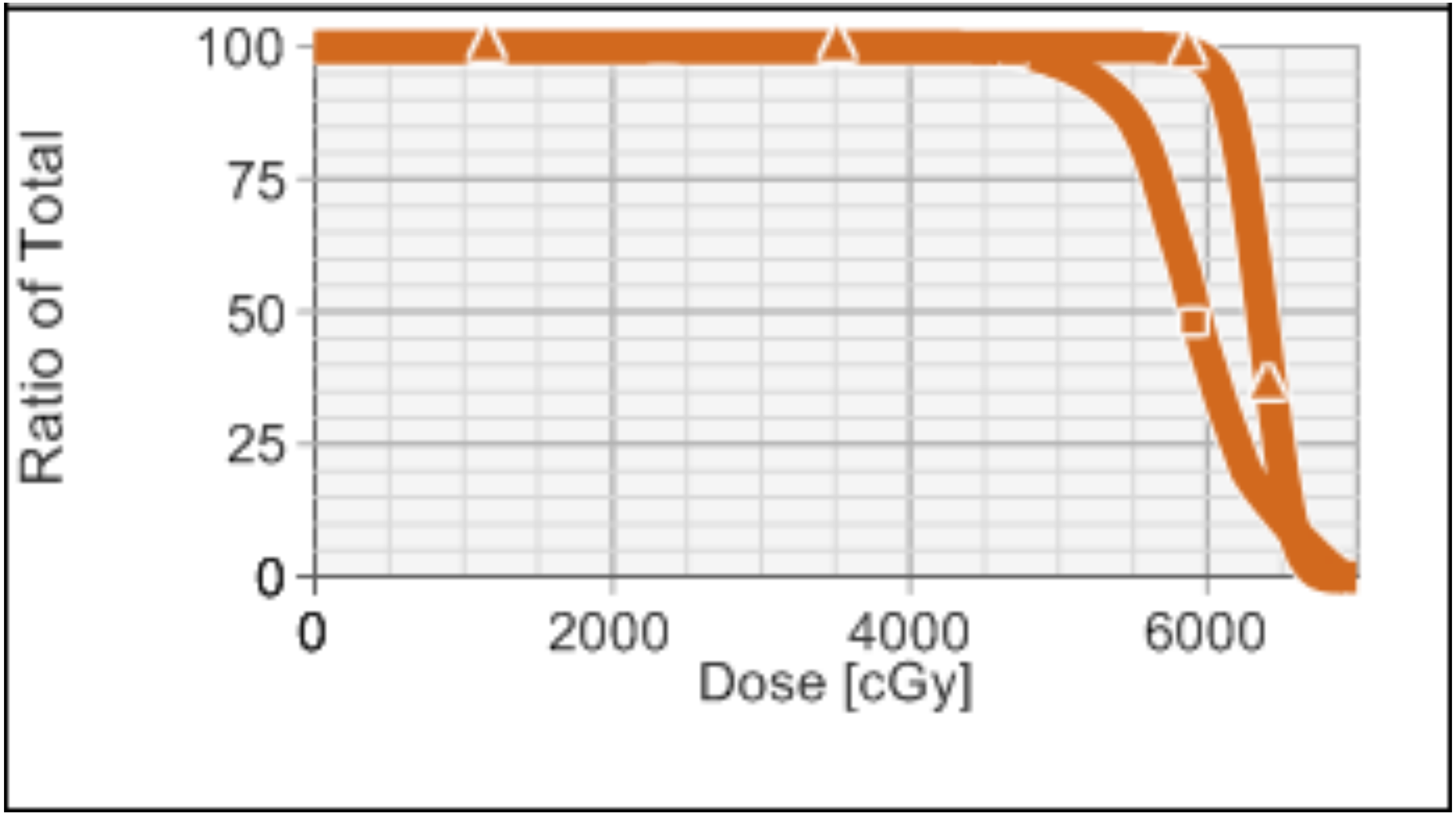
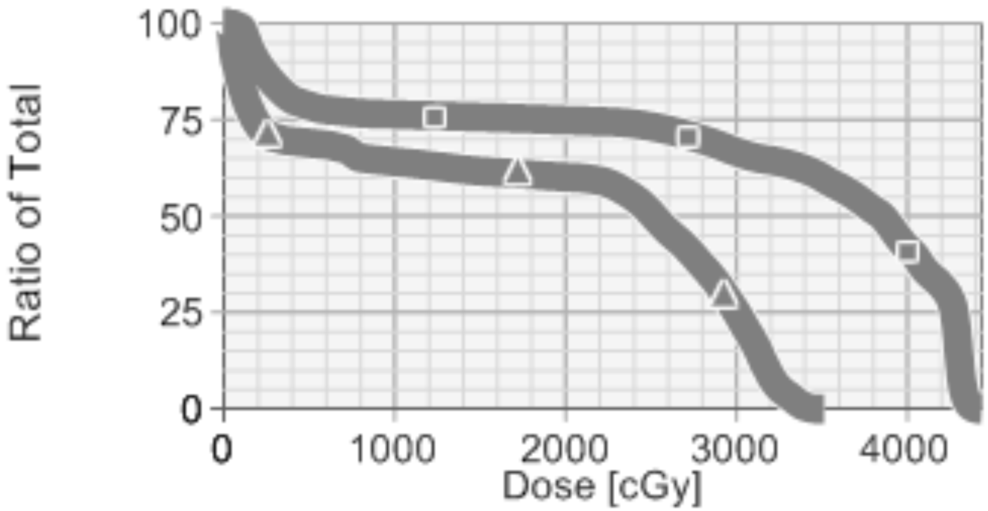
Standard
IMRT
R
L
Standard

PTV DVH: 3D vs IMRT



Spinal Cord DVH: 3D vs IMRT



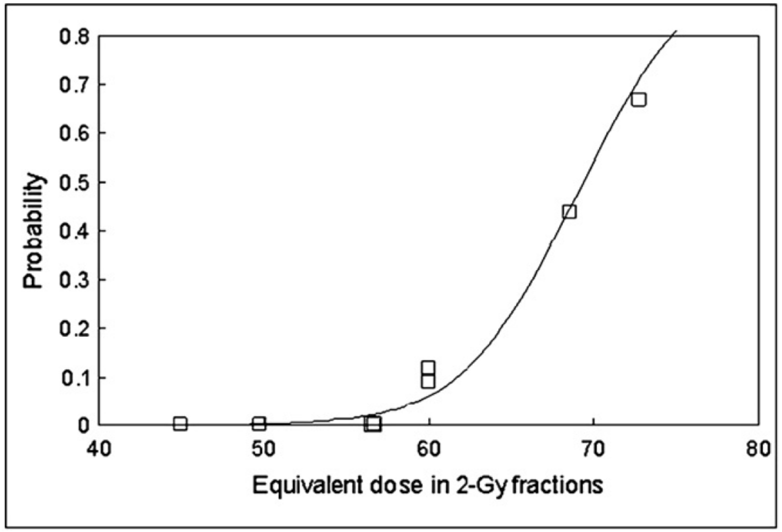
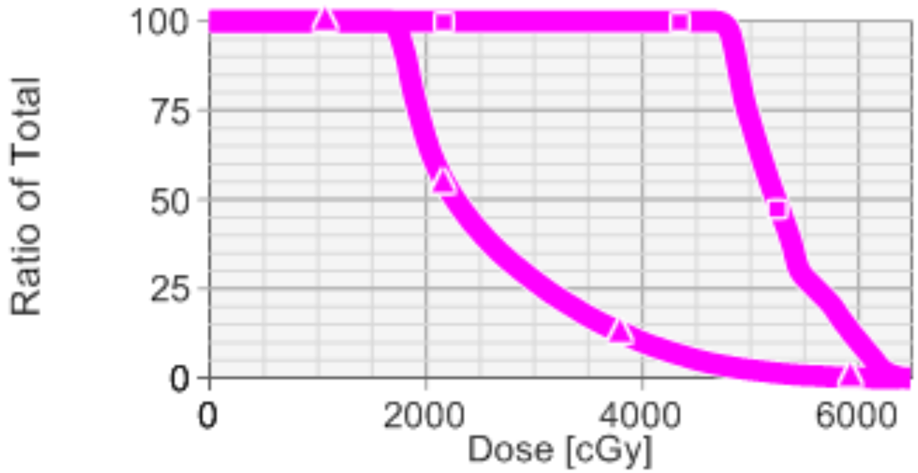
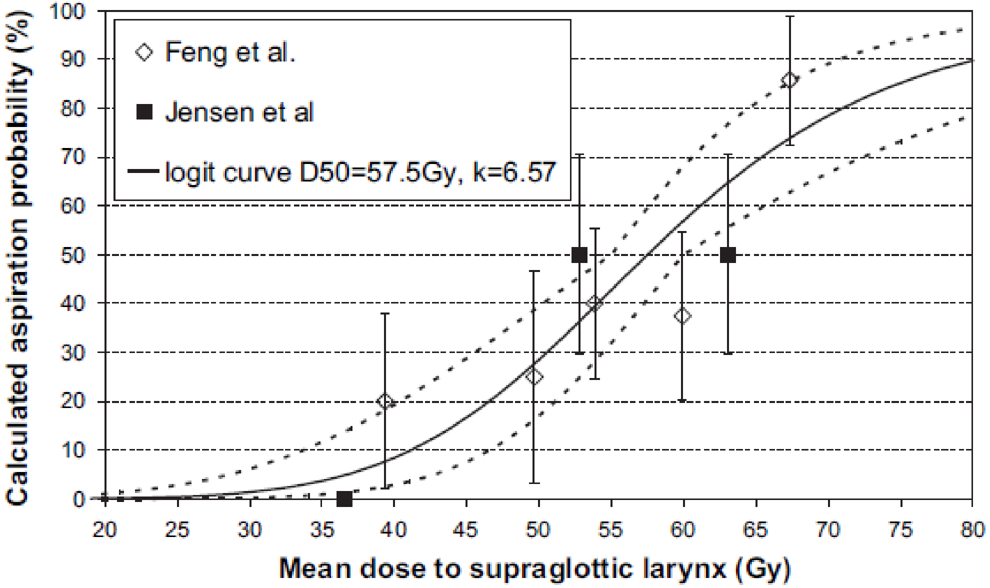


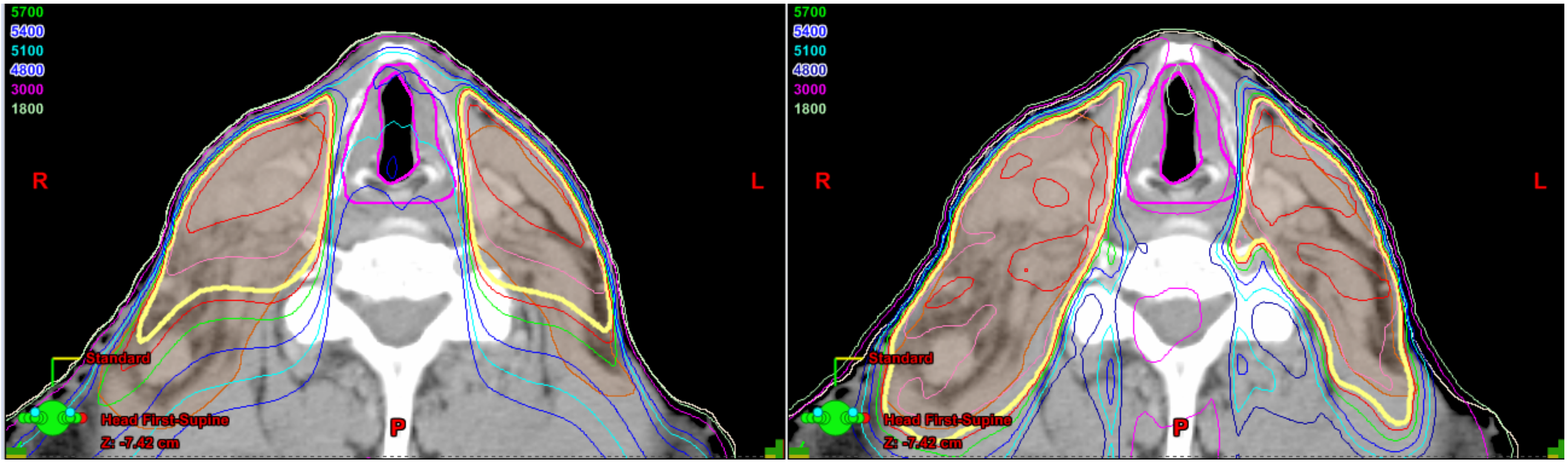
Fig. 1. The dose–response function for the myelopathy of the cervical spinal cord and data points (□) derived from Table 1. The probability of myelopathy was calculated from the data in Table 1, adjusted for estimated overall survival per (18).

Larynx DVH: 3D vs IMRT

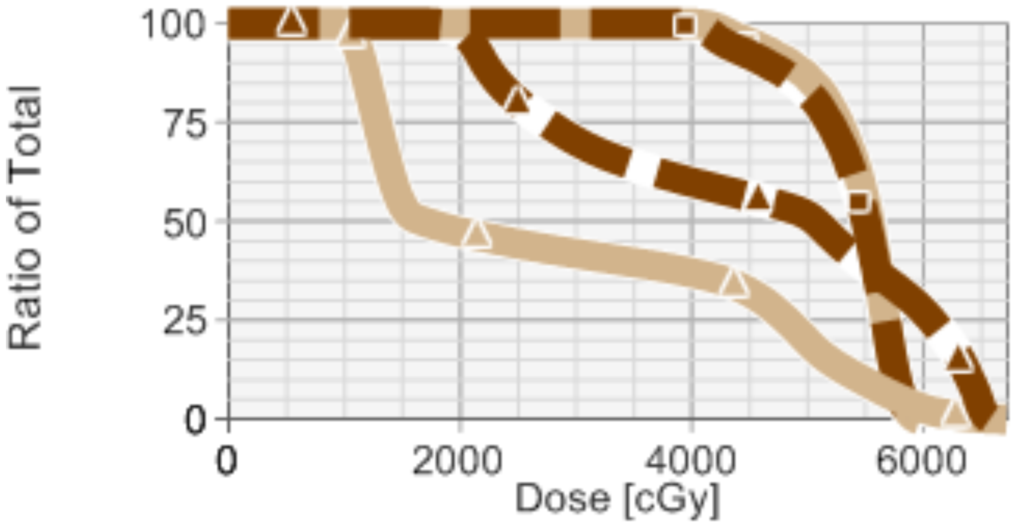
Mean dose: 3D: 53Gy
IMRT: 26Gy

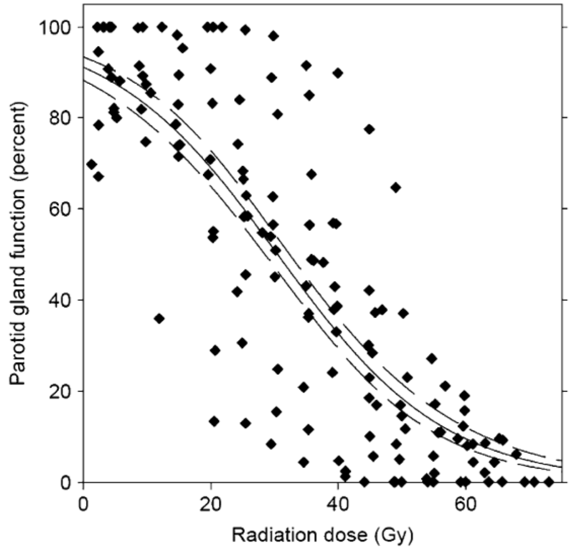


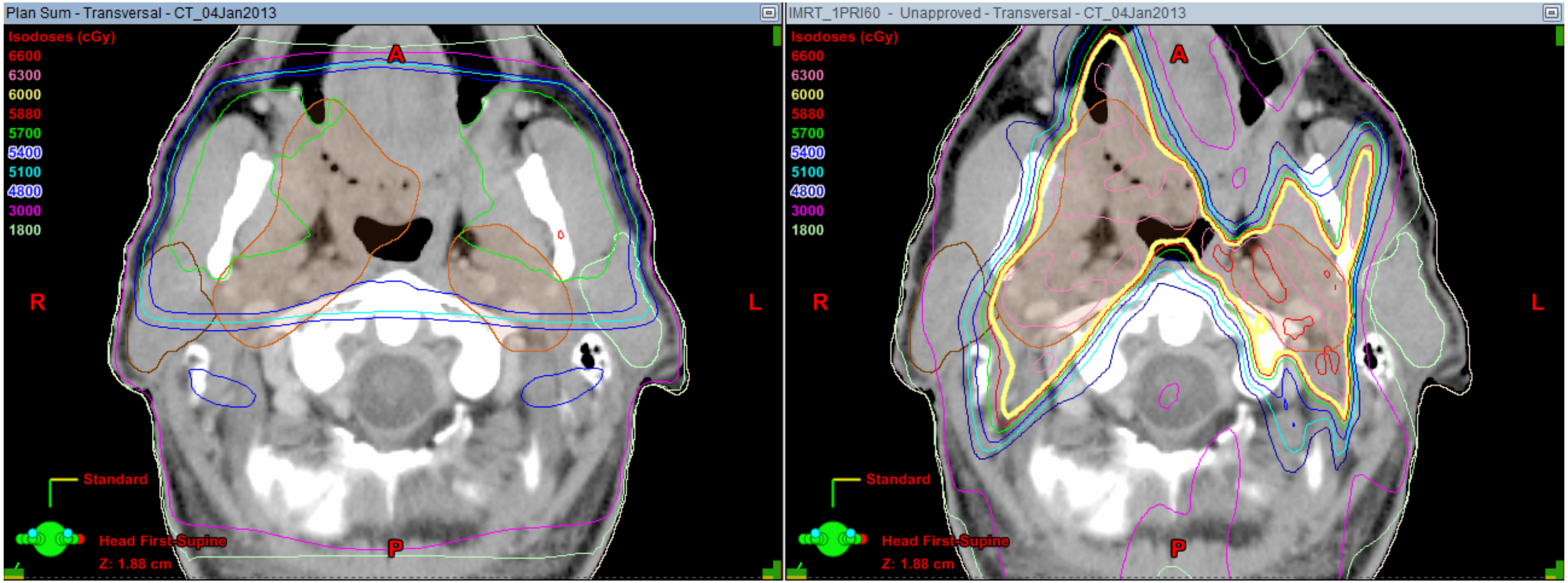


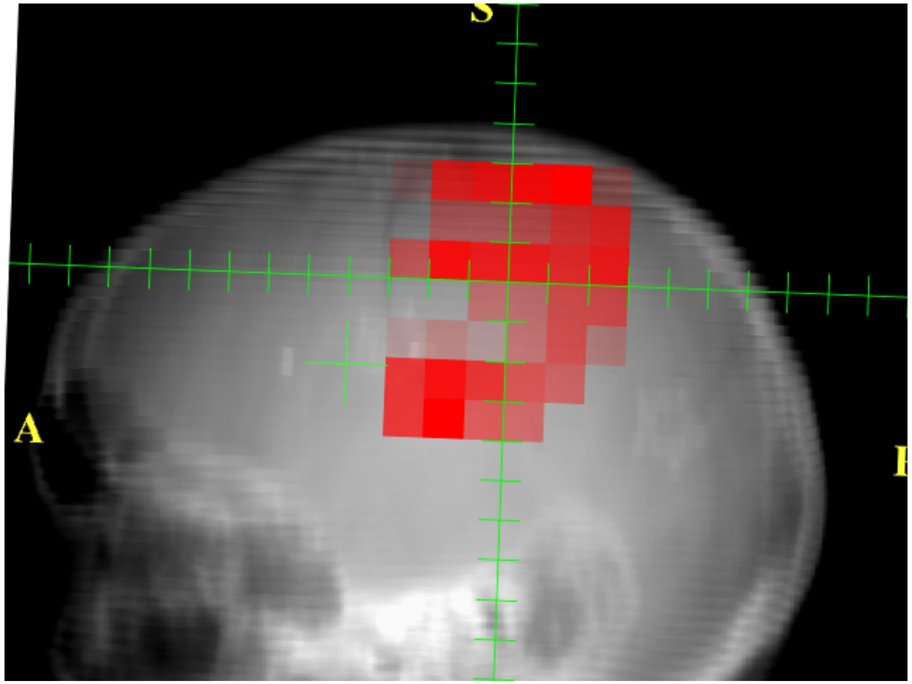


Parotid DVH: 3D vs IMRT



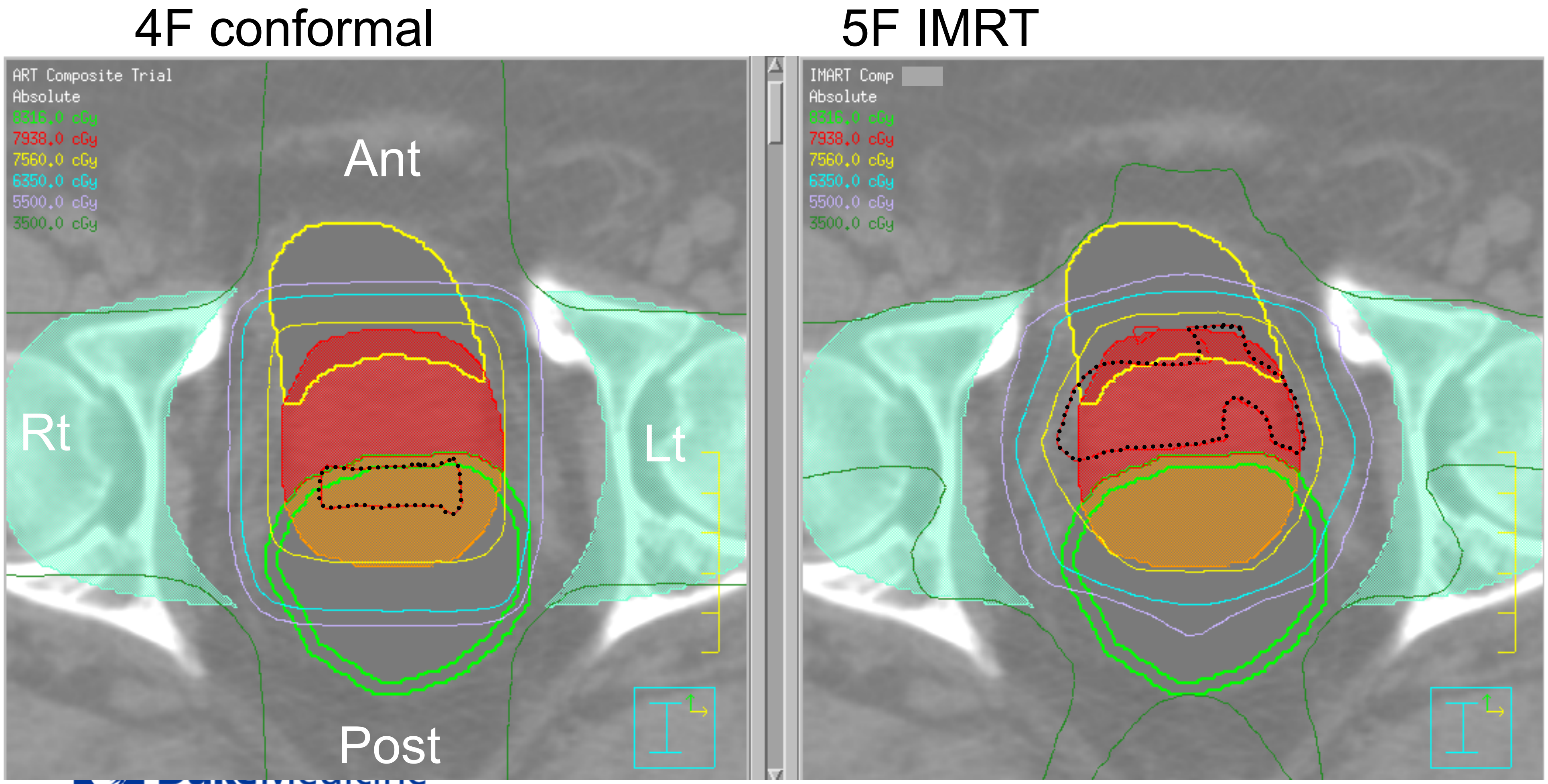






Intensity Map for an IMRT beam superimposed on patient DRR (left) and reflected in hair loss on patient scalp (right)

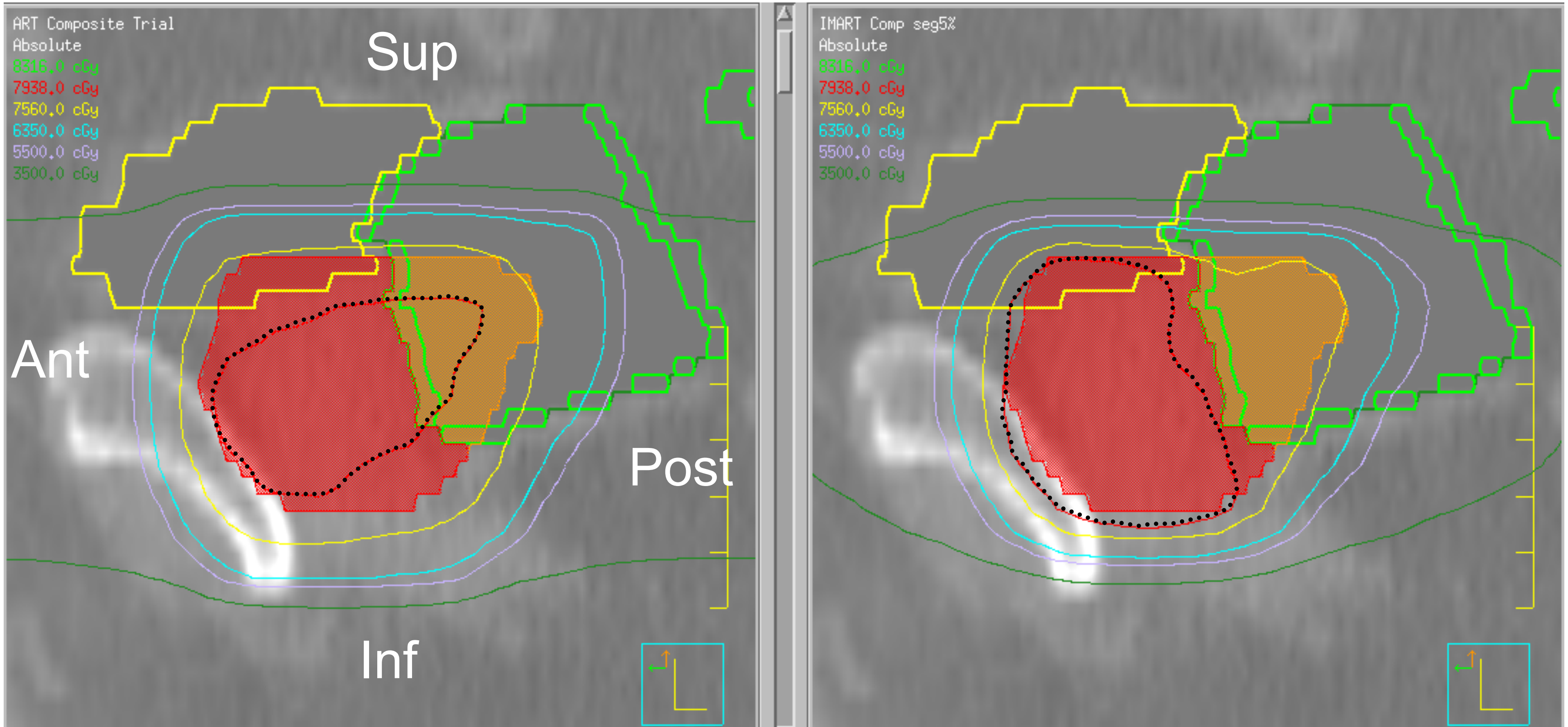
What can IMRT achieve in prostate Tx ?



Axial views

What can IMRT achieve in prostate Tx ?

4F conformal plan | 5F IMRT plan



Saggital views

IMRT vs conformal DVH

Rectal wall

Bladder

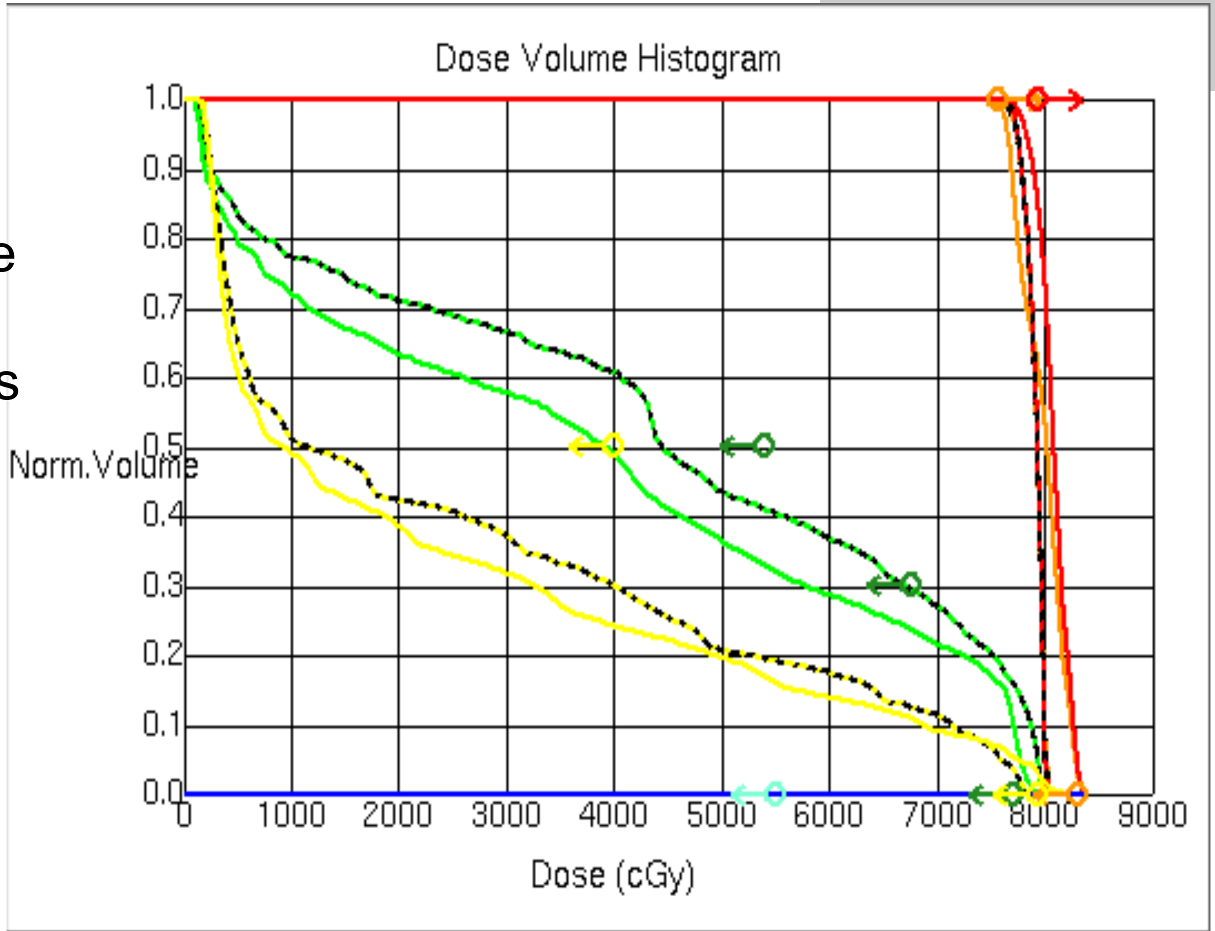
CI-PTV

CI-PTV no rect

In IMRT plans typically ..: -

- PTV less homogenous
- Modest sparing OAR regions that overlap with the PTV

•Significant sparing of OARs that don't overlap with the PTV.



Dashed=4F conformal, solid = IMRT

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Some comments on IMRT

- Better conformity -> may be easier to miss the target ?!
  - Potentially a significant problem
  - First get the margins correct, then implement IMRT
- Beam selection can be non-intuitive
- Tendency to use more beams not less !
- Typical MUs for an IMRT plan are 3-5 times higher
  - Tendency to use lower energy (reduce neutron)
- Tendency to ‘over-stress’ IMRT planning
  - Give the optimization a consistent set of objectives
  - Avoid extreme weighting etc

Summary of IMRT

Advantages

- Ability to produce remarkably conformal dose distributions
- Dose escalation (improvement in local control)
- Decreased dose to surrounding tissues (reduction in complications)

Disadvantages

- Planning is labor intensive
- Extended delivery time (typically)
- Danger of being too conformal
- Generally more inhomogeneous dose distribution
- Increased MU$\rightarrow$ increased whole body dose & increased room shielding

References

- INTENSITY-MODULATED RADIOTHERAPY: CURRENT STATUS AND ISSUES OF INTEREST, Int. J. Radiation Oncology Biol. Phys., Vol. 51, No. 4, pp. 880–914, 2001
- Optimized Planning Using Physical Objectives and Constraints, Thomas Bortfield, Seminars in Radiation Oncology, Vol 9, No 1 (January), 1999:pfl 20-34
- Image Guided Radiation Therapy (IGRT) Technologies for Radiation Therapy Localization and Delivery, Int J Radiation Oncol Biol Phys, Vol. 87, No. 1, pp. 33e45, 2013
- Image-guided radiotherapy: rationale, benefits, and limitations, *Lancet Oncol* 2006; 7: 848–58
- Planning in the IGRT Context: Closing the Loop, Semin Radiat Oncol 17:268-277

Thank You!