Intensity Modulated Radiation Therapy: Technology and Process

ICPT School on Medical Physics for Radiation Therapy

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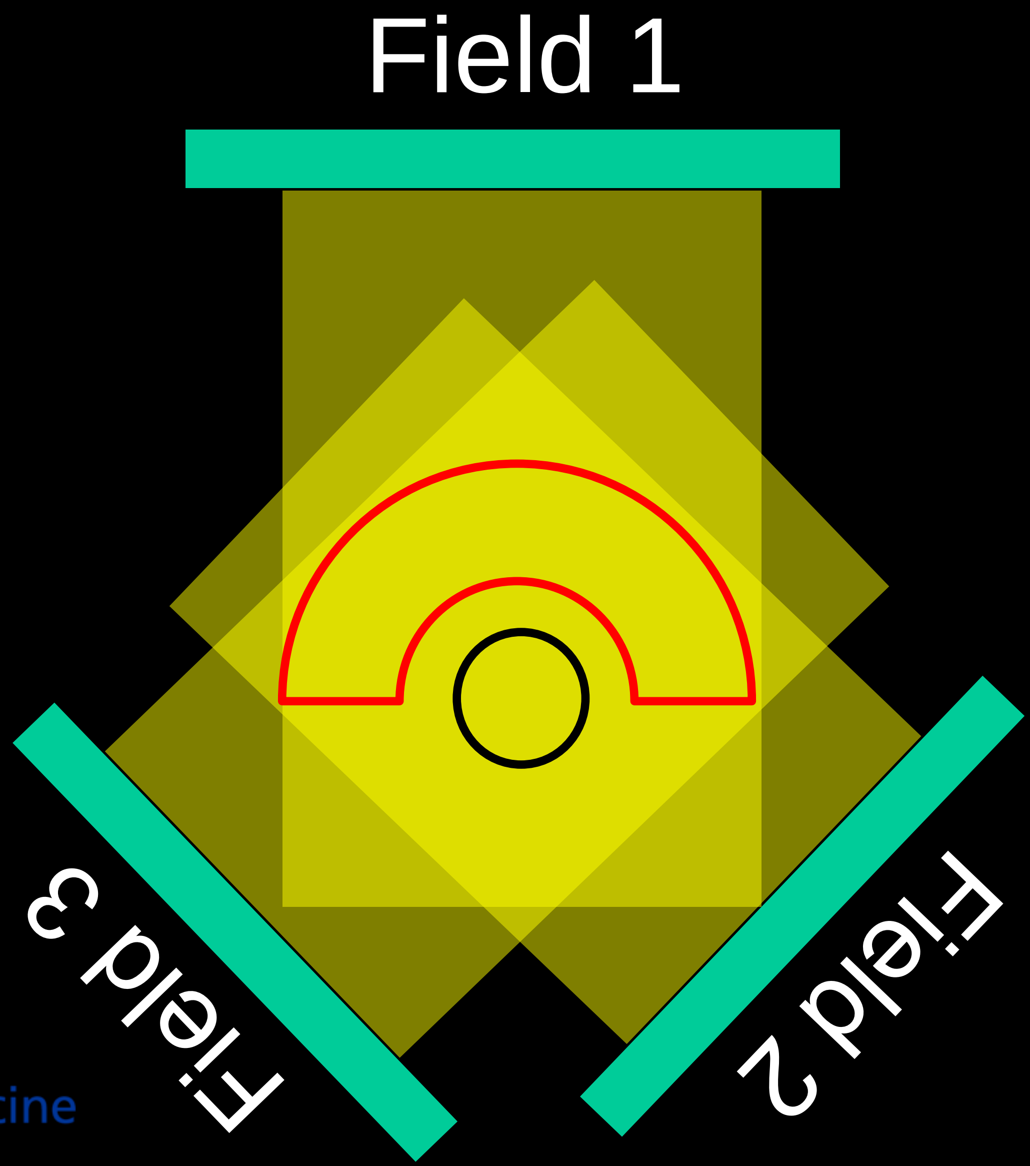
Good morning!

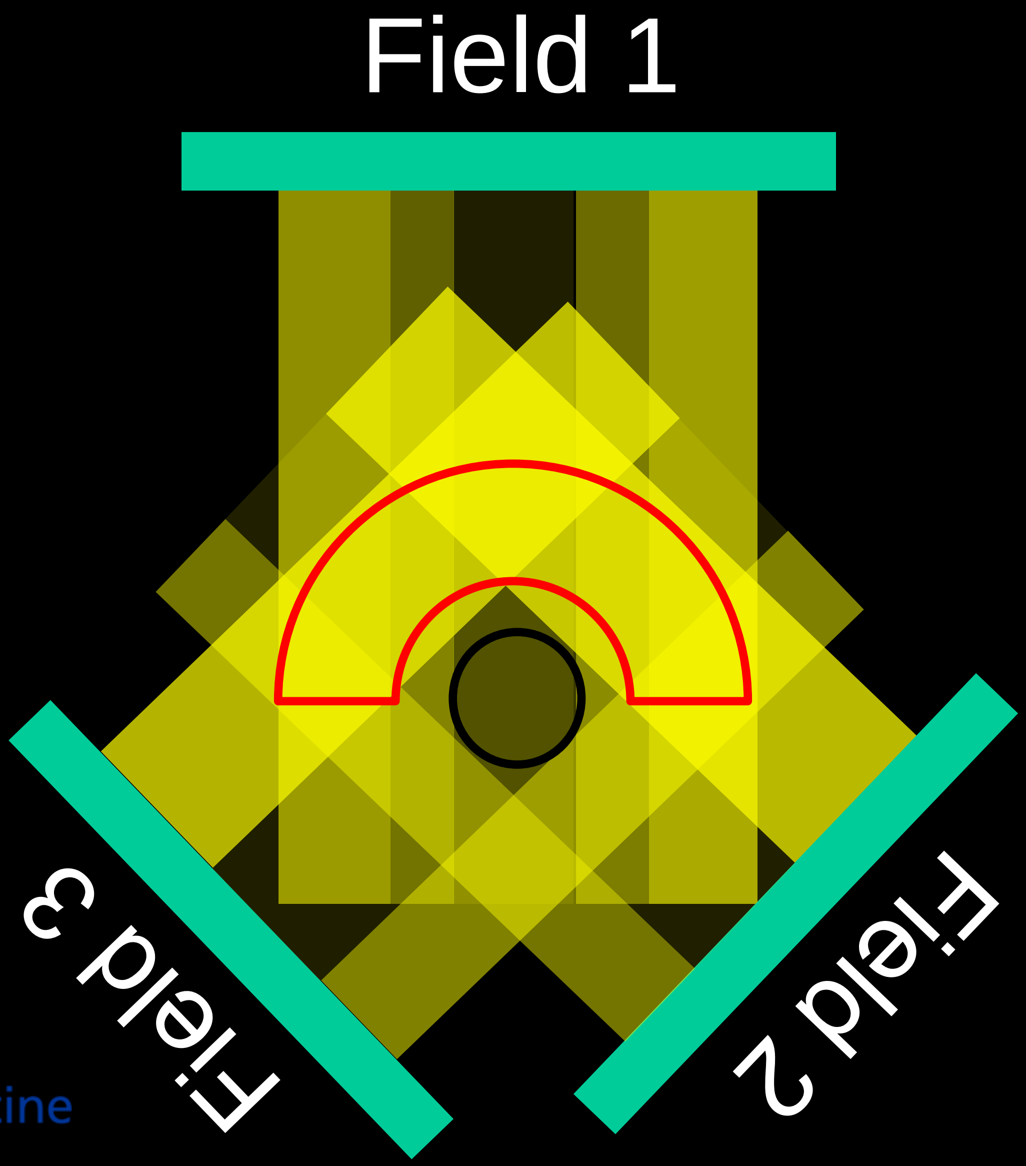
Topics

- Concept
- Delivery Technologies
  - – Compensator Based IMRT
  - – Jaw Based IMRT
  - – MLC Based IMRT:
    - Step & Shoot (Static) IMRT
    - Dynamic IMRT (sometimes called sliding window)

3D Radiation Therapy



IMRT Radiation Therapy



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IMRT Radiation Therapy

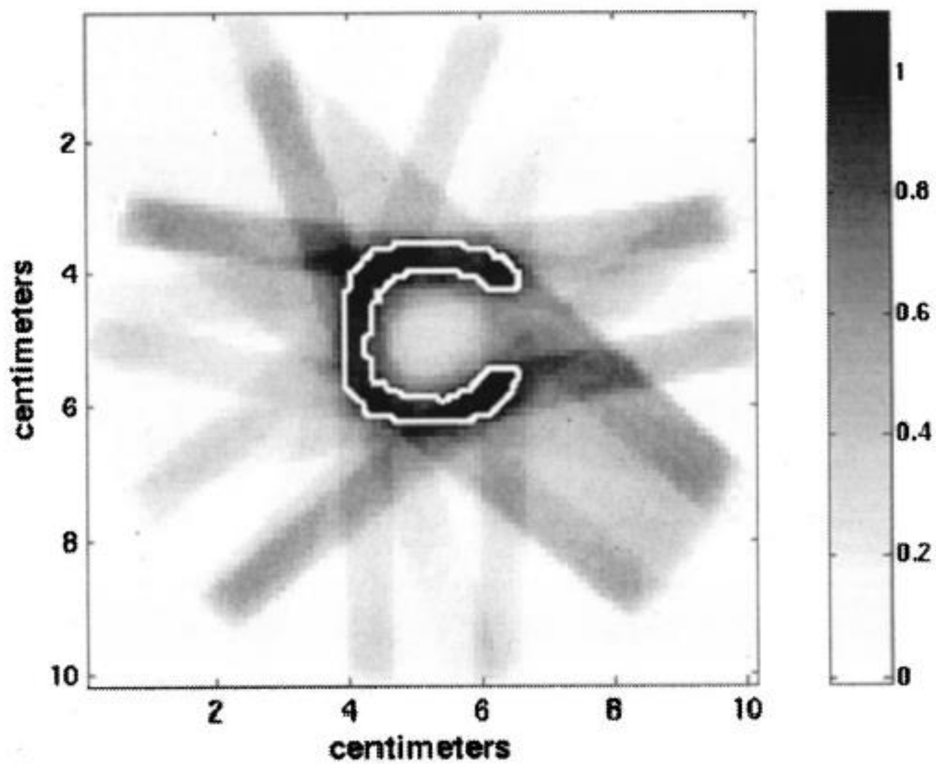

FIG. 9. An optimized dose distribution for a c-shaped target with a centrally located sensitive structure. In this case seven beams angles were used with seven apertures per beam direction. The target is outlined in white.

Medical Physics, Vol. 29, No. 6, June 2002

Intensity Modulated Radiation Therapy (IMRT)

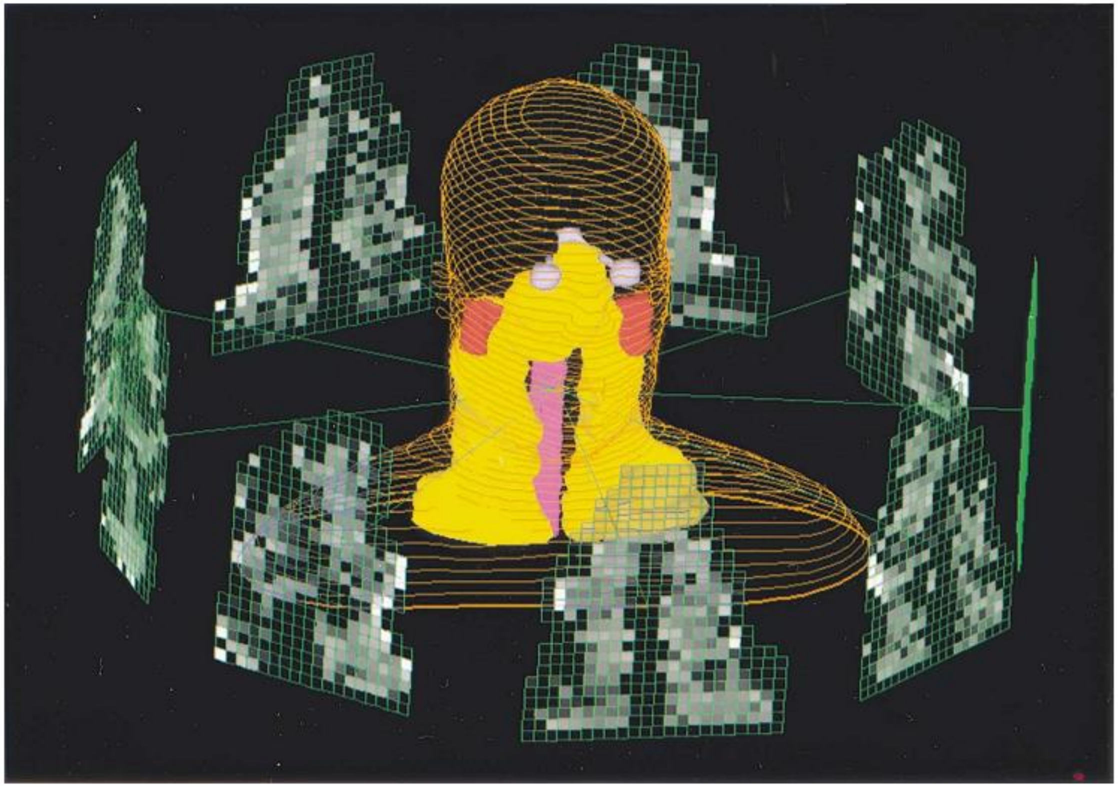

Fig. 1. Advanced form of 3D-CRT—IMRT—which is based on the use of optimized non-uniform radiation beam intensities incident on the patient. Shown is a 3D view of the patient, the PTV, spinal cord, and parotid glands, and the 9 intensity modulated beams (with gray levels reflecting the intensity value)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

Int. J. Radiation Oncology Biol. Phys., Vol. 51, No. 4, pp. 880–914, 2001

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

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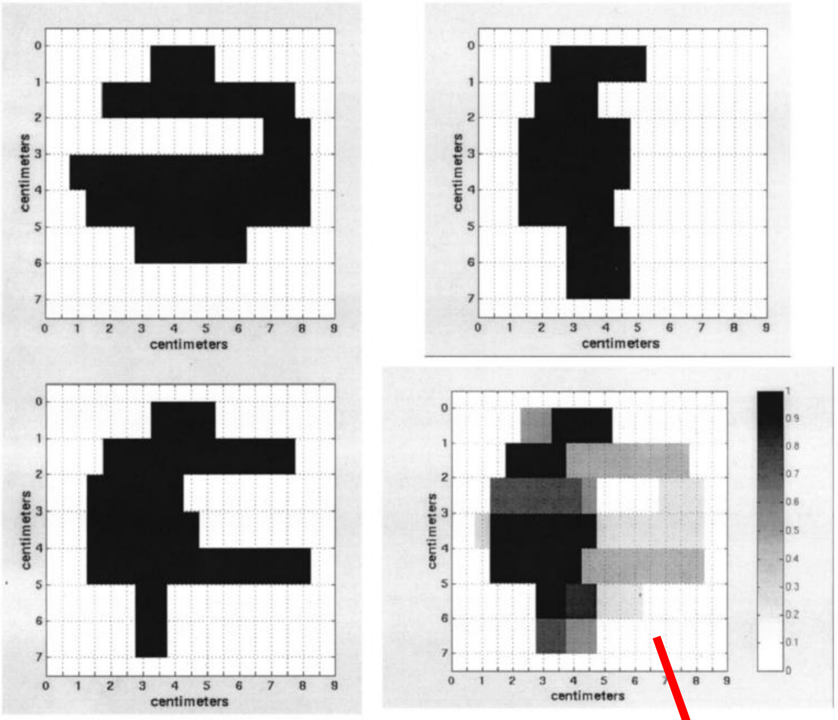
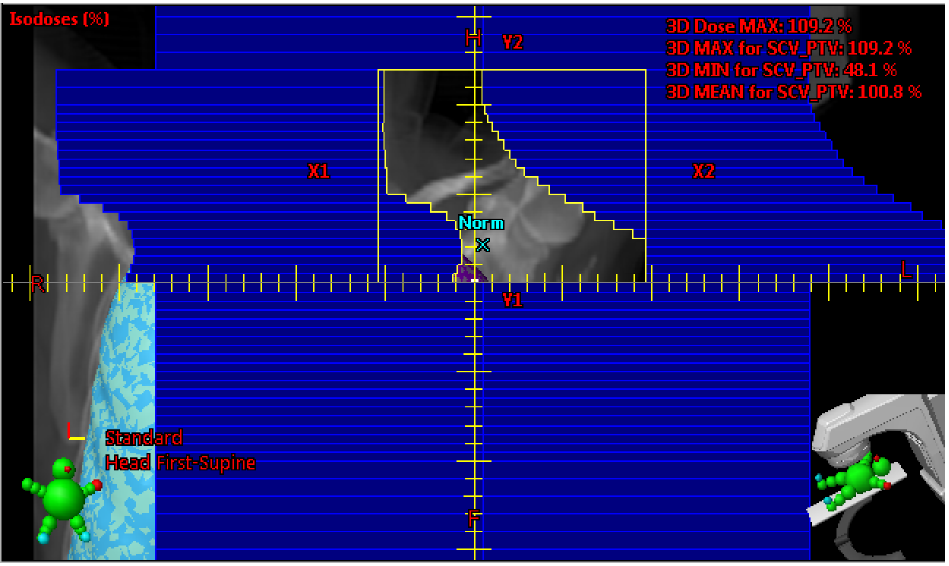
Forward Planned IMRT

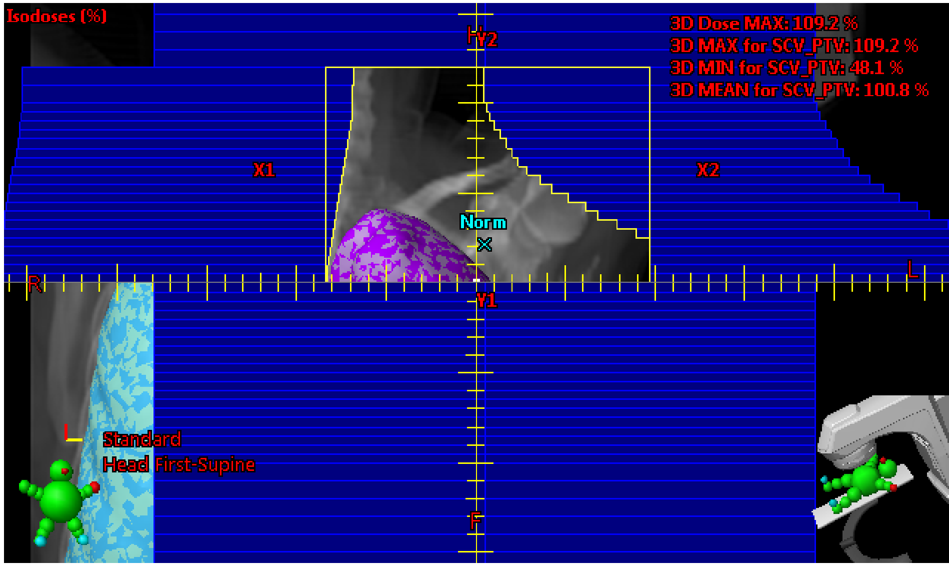
- Method 1: define fluence manually
  - fluence is defined by user
  - MLC leaf sequence is calculated to create the fluence
- Method 2: create multiple subfields (same beam geometry)
  - manually define MLC positions & relative weighting for each subfield

example of subfields

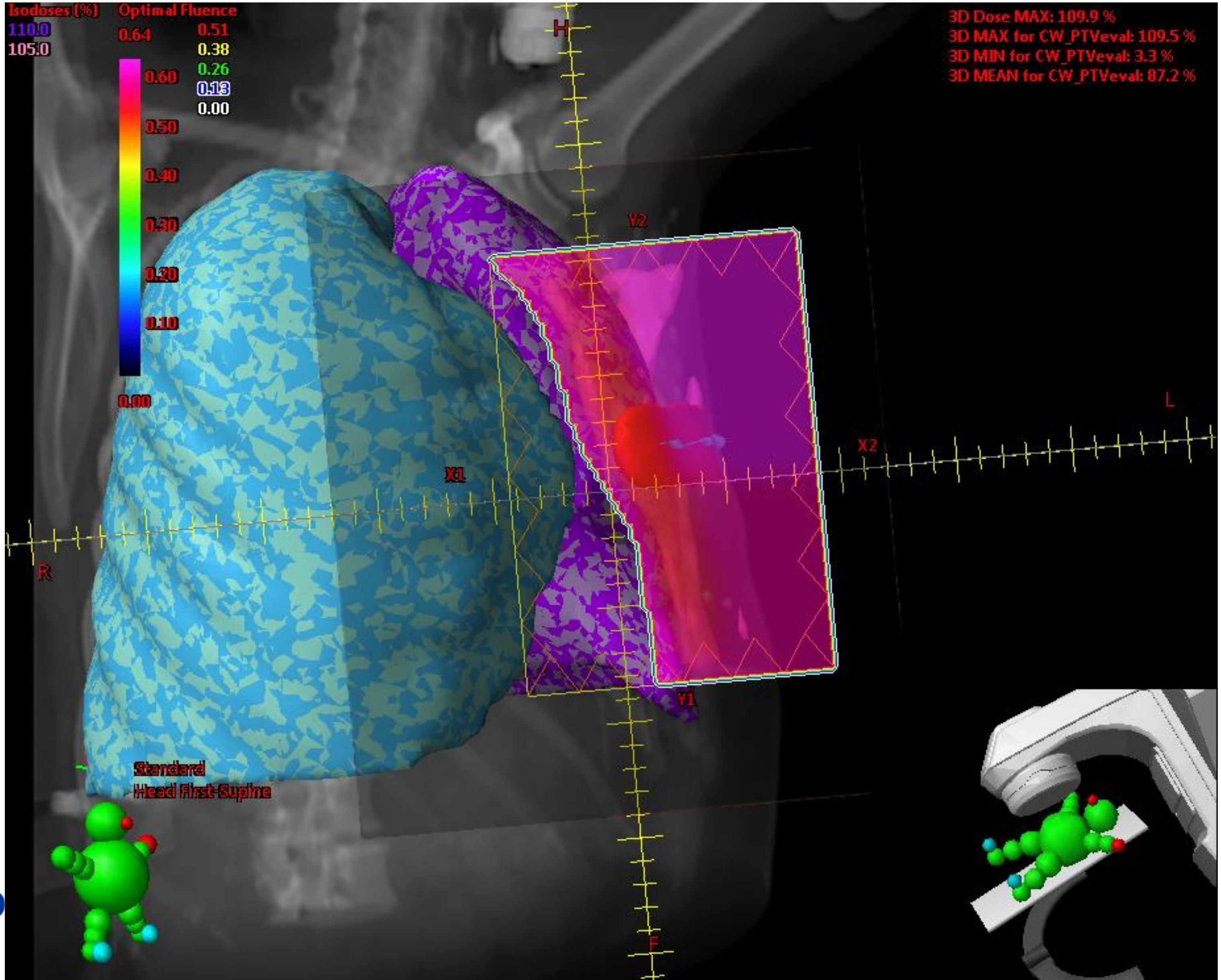


Subfields Example

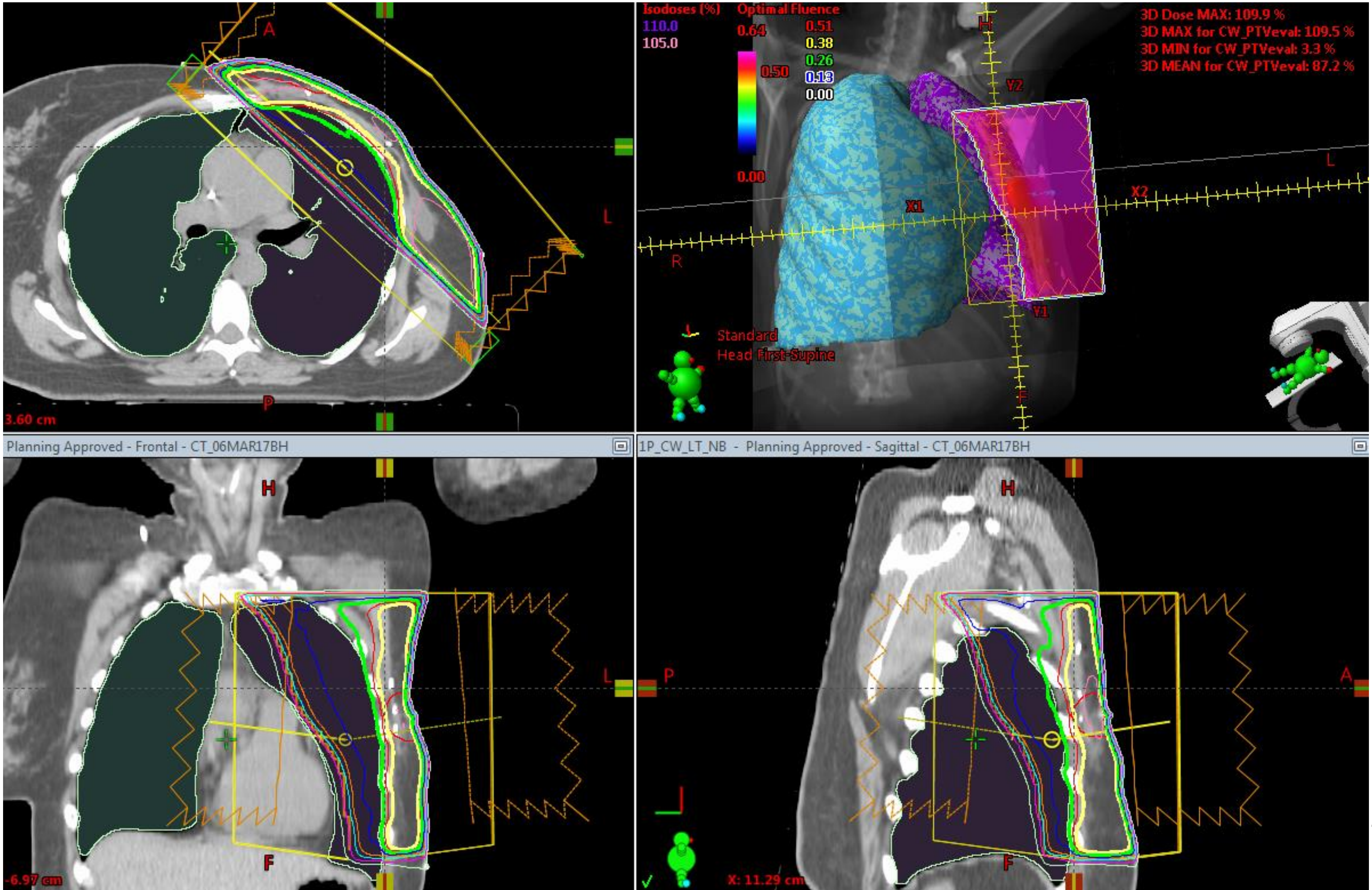




Forward Planned IMRT Example



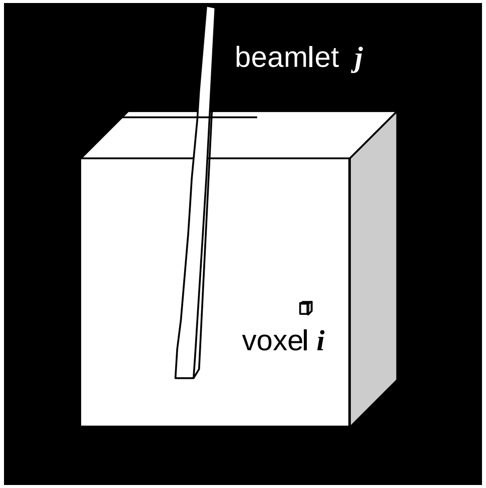
Forward Planned IMRT Example



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

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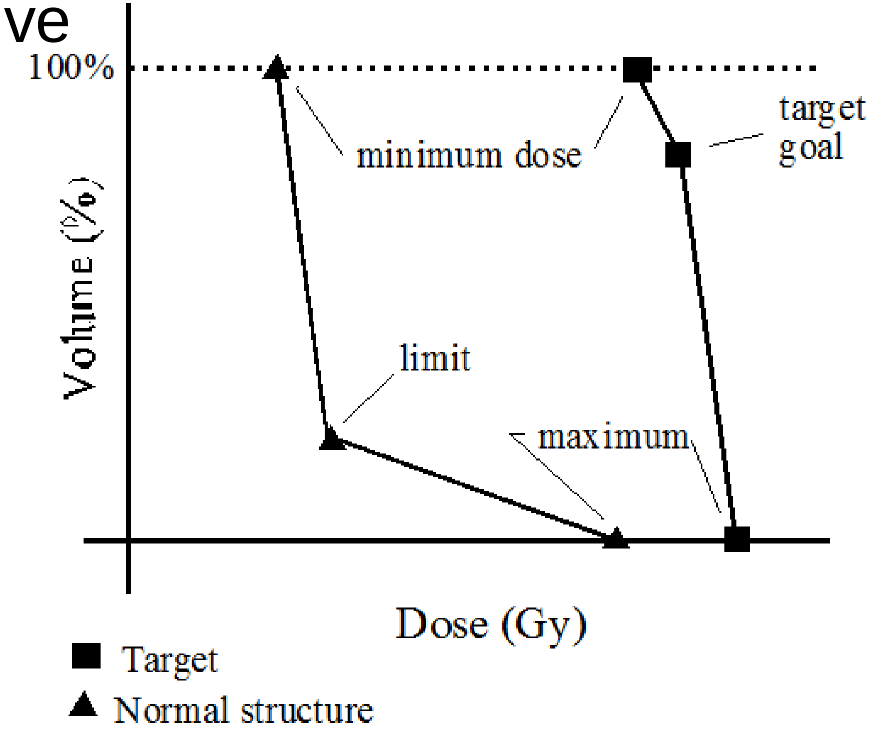
Inverse Planning: Optimization

- 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

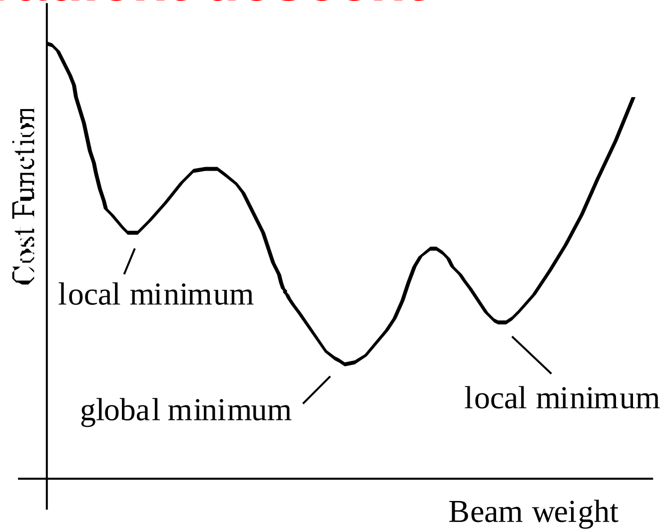
- Dose criteria typically defined using DVH
- Use cost function that quantifies how close the dose from the current beamlet weighting is to the objective



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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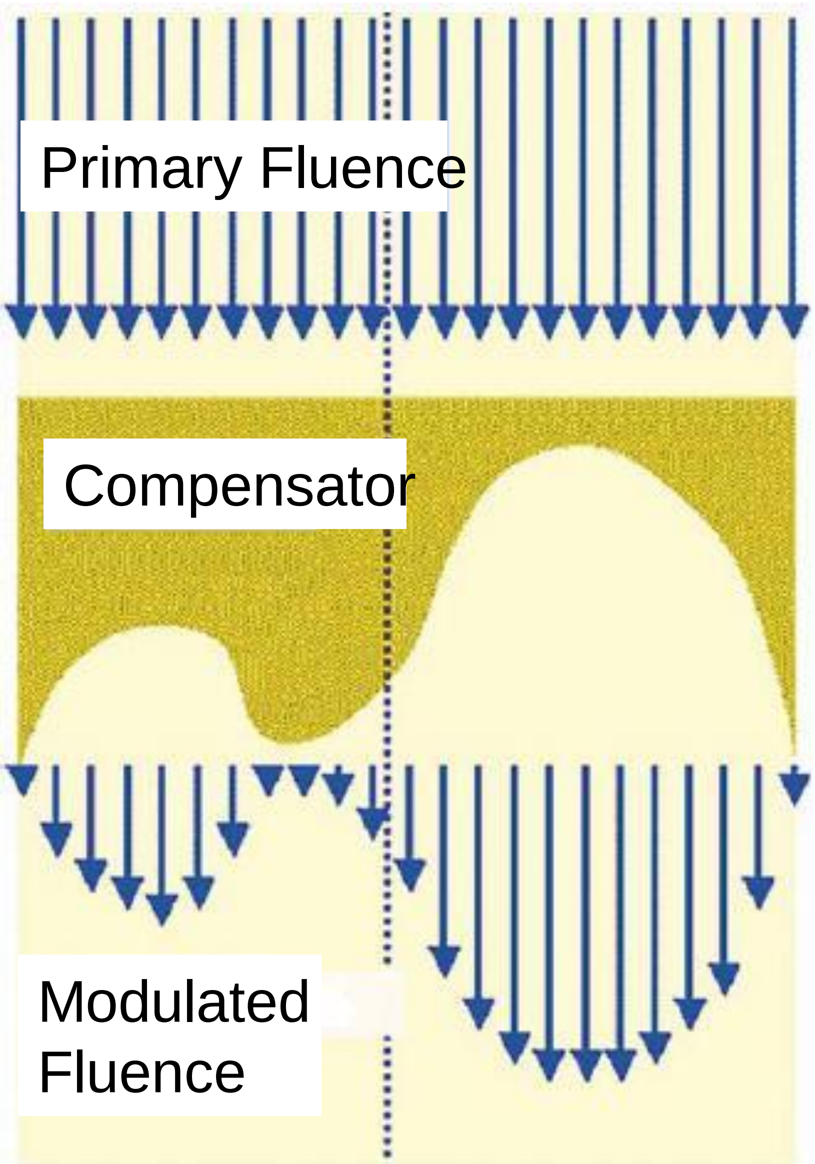
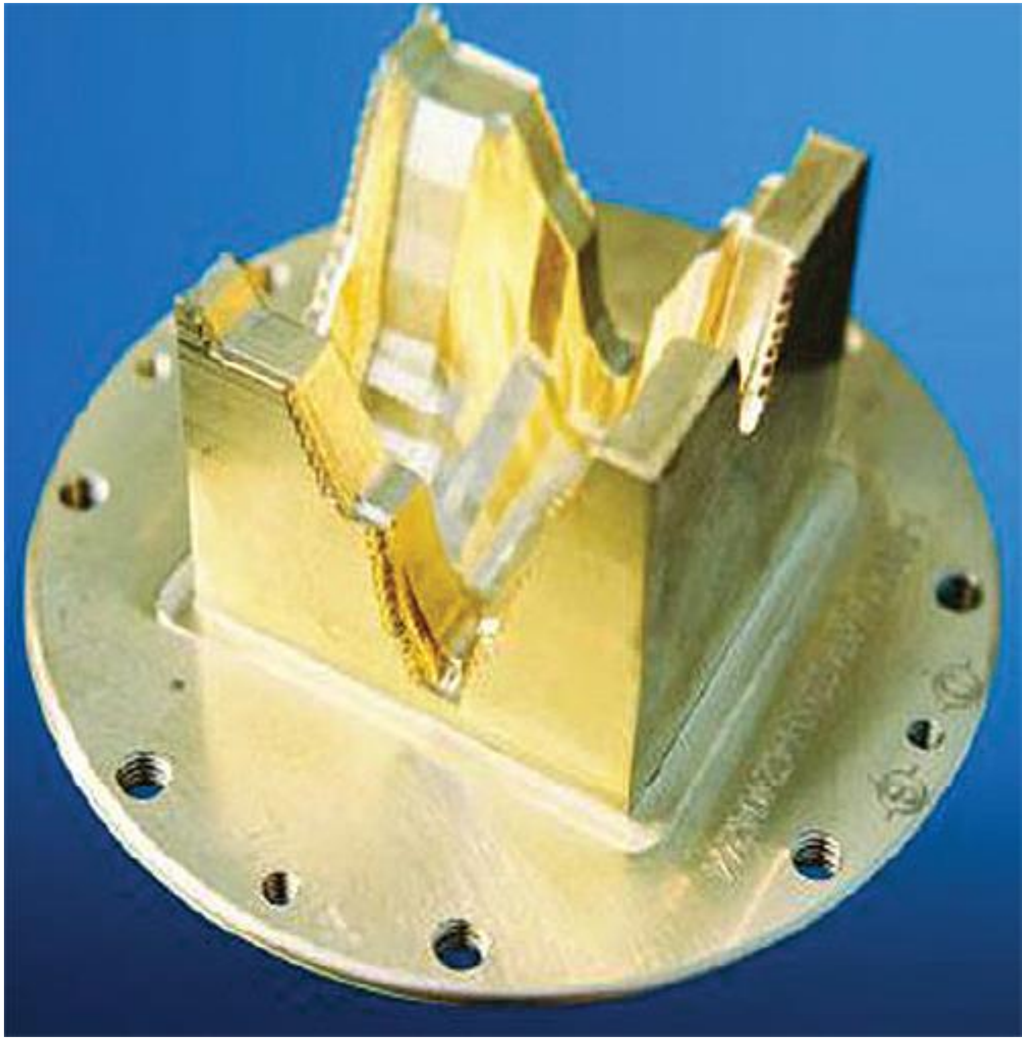
How to deliver the fluence?

- Physical Compensators
- Jaw Sequence
- MLC Sequence
  - leaf sequence to match ideal fluence
    - Multiple Static Segments
    - Dynamic MLC Trajectory
  - 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

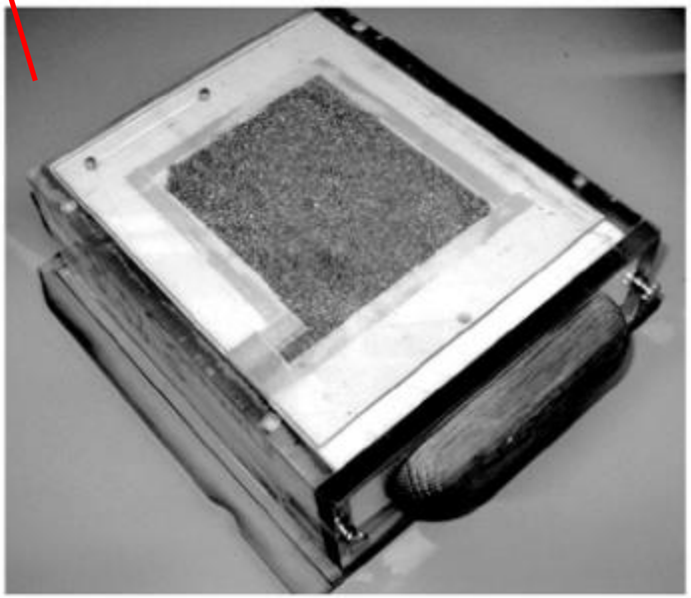




IMRT Methods: Physical Compensators

reusable tin granules & compensator box

disposable styrofoam mold



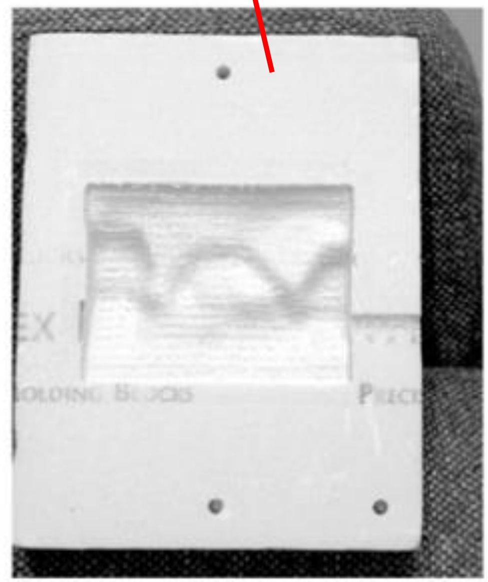


FIG 4. Compensator box with a tin granule-filled compensator enclosed (left) and a Styrofoam compensator mold (right). The three reference holes on the mold and the matching set on the box are used for easy verification of the compensator orientation in the box. The compensator is designed to be inserted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

JOURNAL OF APPLIED CLINICAL MEDICAL PHYSICS, VOL. 5, NO. 3, SUMMER 2004

IMRT Methods: Physical Compensators

Advantage: simple implementation

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

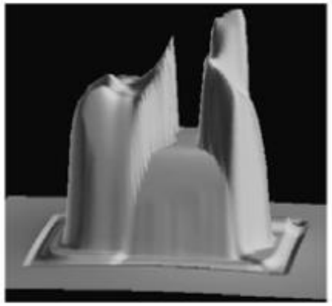
Disadvantage: lack of automation

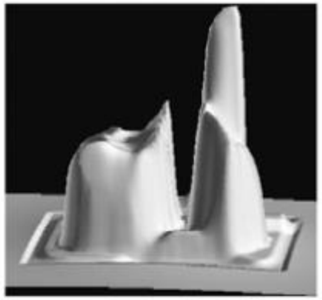
- each field requires a custom compensator
- need to enter room per field
- Limited modulation

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

Newer development: 3D Printed Compensators

- Avelino, Samuel R., Luis Felipe O. Silv and Cristiano J. Miosso. "Use of 3D-printers to create intensity-modulated radiotherapy compensator blocks." *Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE*. IEEE, 2012.
- 3D print mold
- Cerrobend compensator
- http://ieeexplore.ieee.org/document/6347293/

A Continuous 3D-Printing Technique for Rapid Fabrication of Personalized Compensator Devices

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- Preliminary technology for fast 3D printing
- resin based compensators

Jaws-only IMRT using direct aperture optimization

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IV. SUMMARY AND CONCLUSION

Using direct aperture optimization, it is possible to create jaws-only IMRT treatment plans. The jaws-only approach can serve as a viable IMRT delivery technique for clinics without a multileaf collimator. The results demonstrate that in some cases jaws-only IMRT is able to produce similar plan quality to that provided with a traditional multileaf collimator based IMRT. In particular, jaws-only IMRT may prove useful for tangential breast IMRT and in prostate IMRT. For larger targets, complex target shapes, and cases involving multiple prescription levels, it is unlikely that a jaws-only approach will be able to approach typical MLC-based IMRT plan quality. For the five cases included in this study an average treatment time of 18 min was observed. All five jaws-only delivery verifications provided absolute dose measurements that agreed within 5%.

Medical Physics, Vol. 34, No. 1, January 2007

Jaw Only IMRT

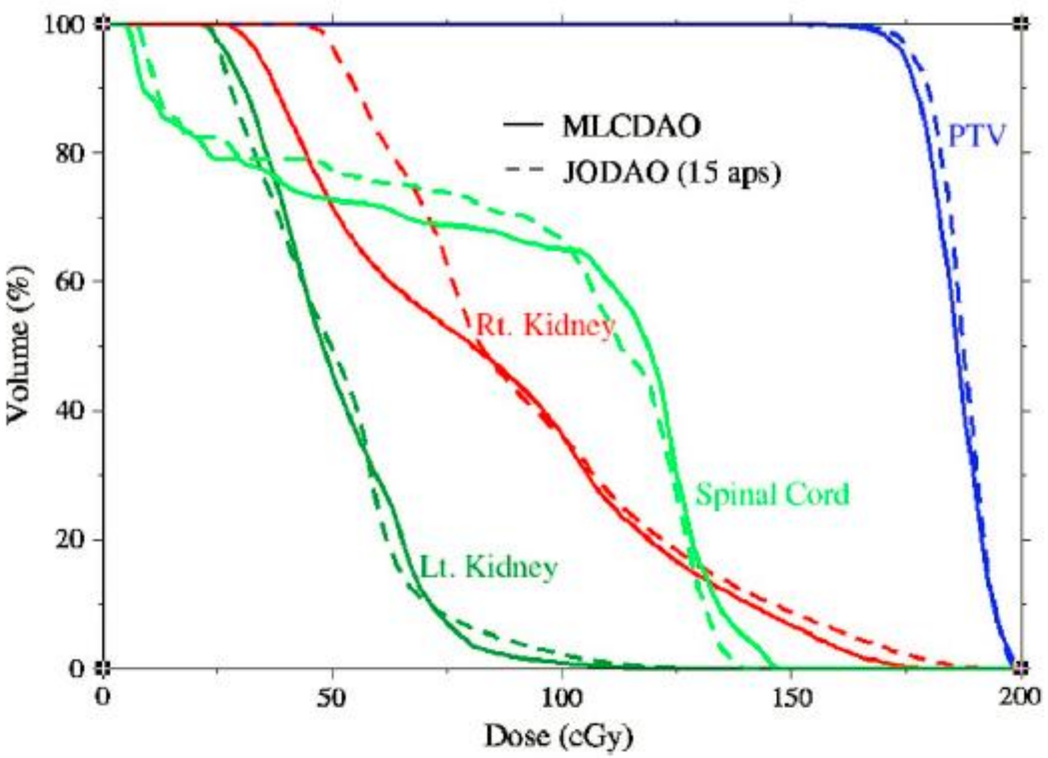

FIG. 2. Dose volume histogram for the pancreas 1 patient. Solid lines denote the MLCDAO plan with seven apertures per beam angle, whereas the dashed lines denote JODAO plan with 15 apertures per beam angle.

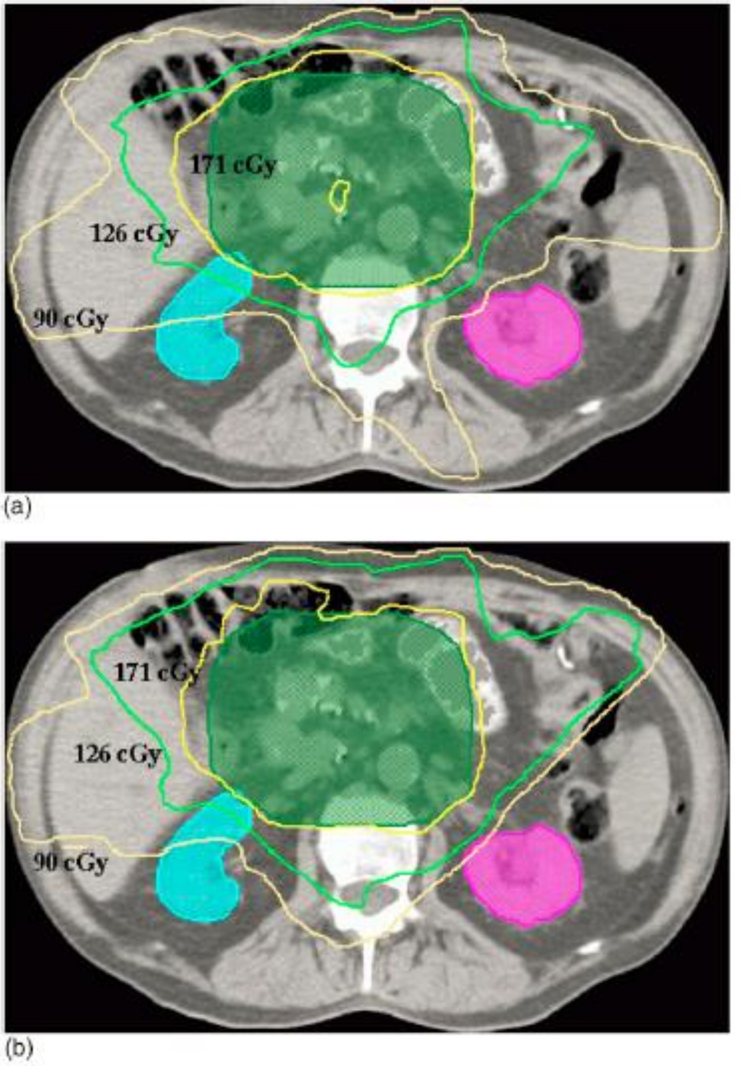

FIG. 3. Comparison of isodose distributions between MLCDAO (a) and JODAO (b) plans for the pancreas 1 patient. The 171, 126, and 90 cGy lines are shown (corresponding to the single fraction prescription dose of 90%, 70%, and 50%).

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Jaw Only IMRT

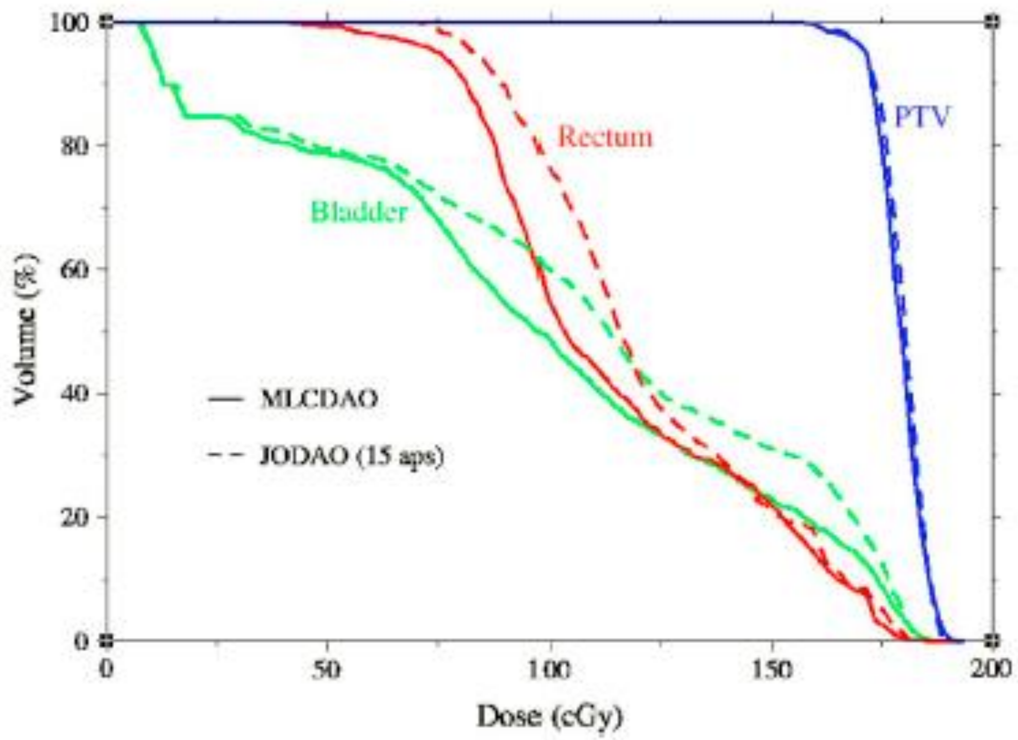


FIG. 7. Dose volume histogram for prostate patient 1. Solid lines denote the MLCDAO plan with five apertures per beam angle, whereas the dashed lines denote JODAO (15 aps) plan.

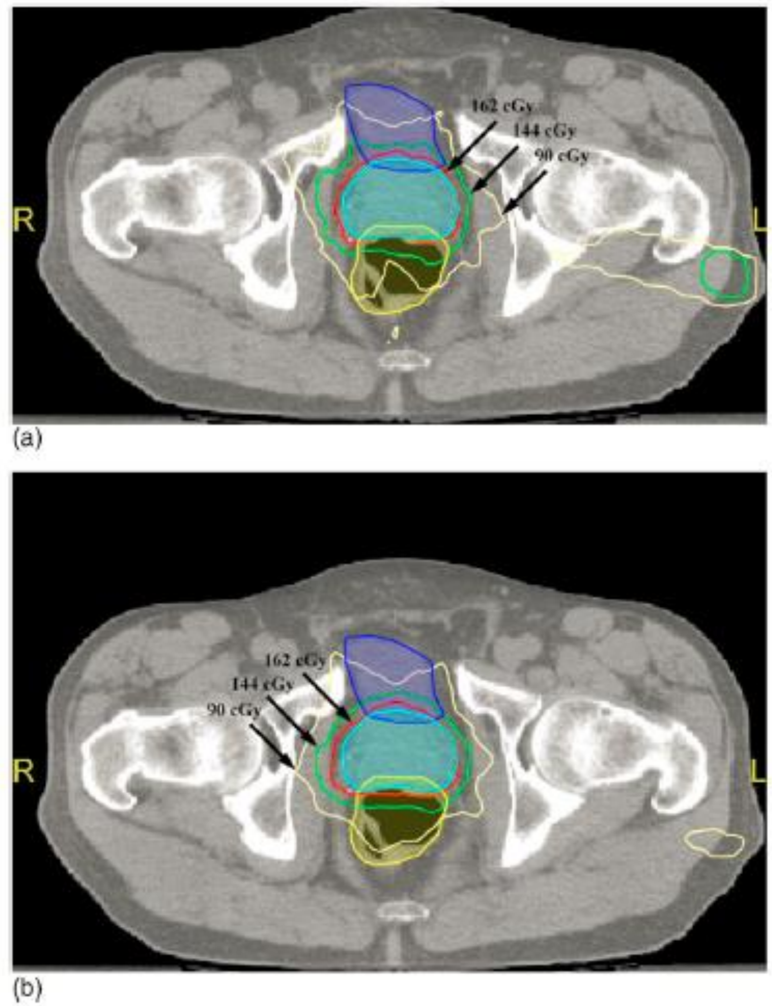


FIG. 6. Comparison of isodose distribution between MLCDAO (a) and JODAO (15 aps) (b) plans for the prostate patient 1. The PTV, bladder, and rectum are shown. Isodose lines shown are 162, 144, and 90 cGy (corre- ...ing to 90%, 80% and 50% of the single fraction prescription dose of ...y).

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

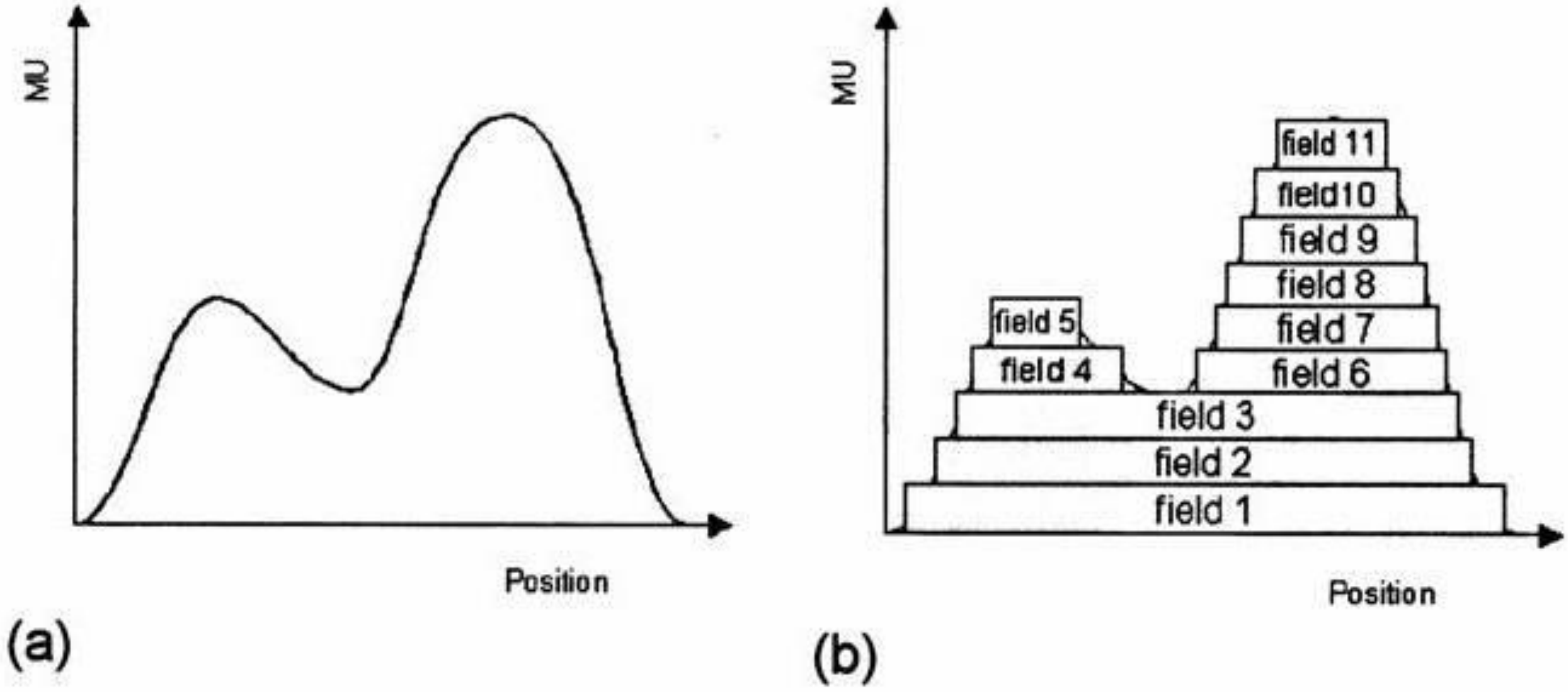
Leaf Sequencing Algorithm:

- 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)



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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)

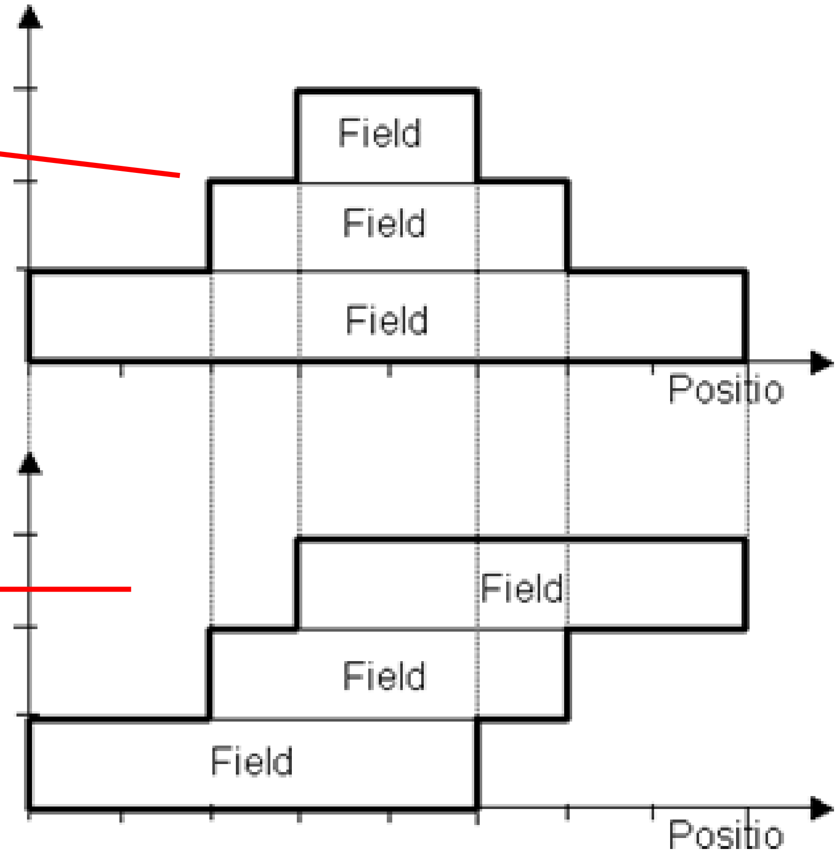
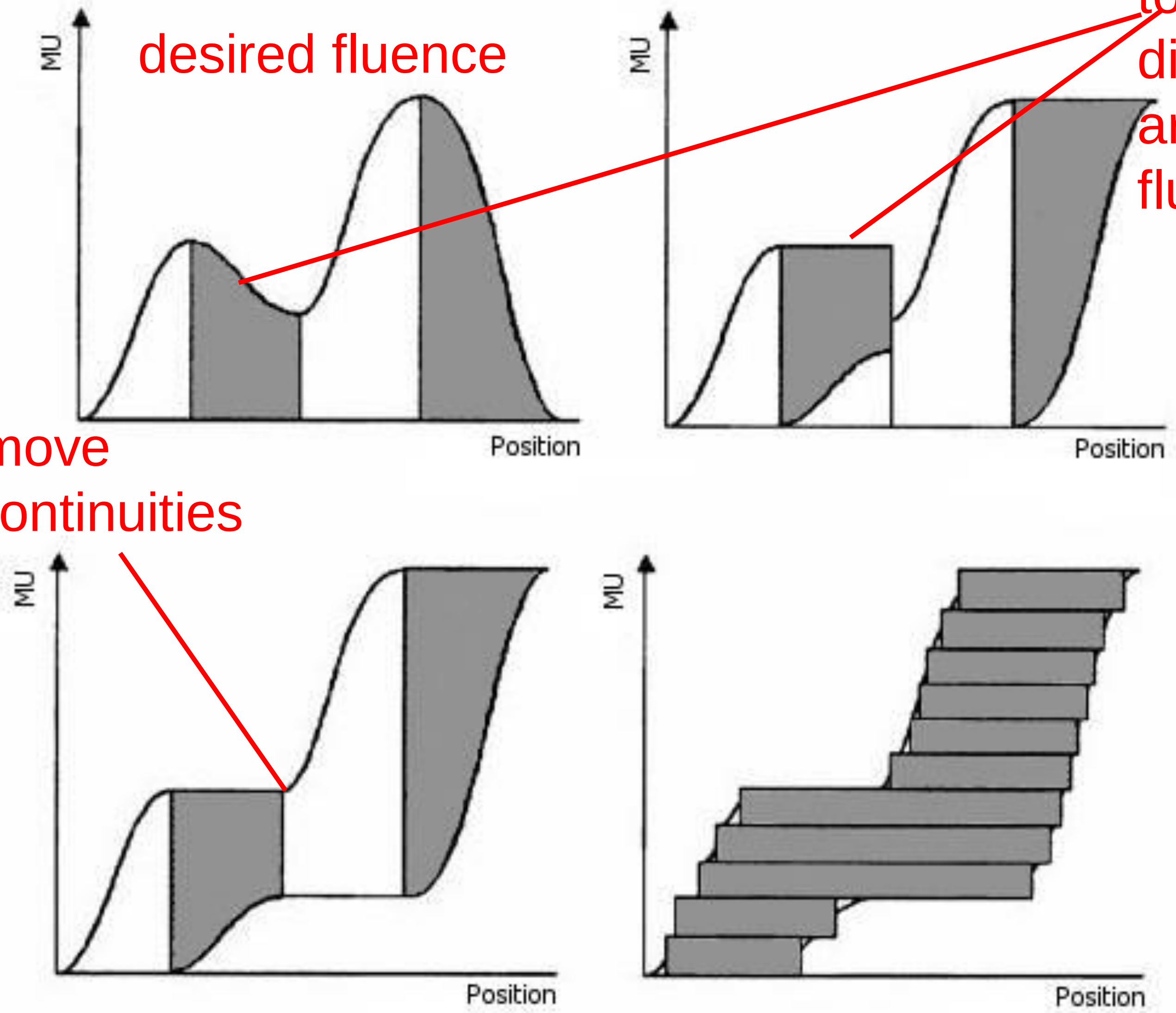


Figure 10.11: The close-in decomposition and the leaf-sweep decomposition illustrated using a simple pyramidal intensity profile

same fluence can be delivered with both methods

IMRT Methods:
Sweeping Leaves for dynamic MLC



desired fluence

to create a single direction of travel areas of decreasing fluence are offset

remove incontinuities

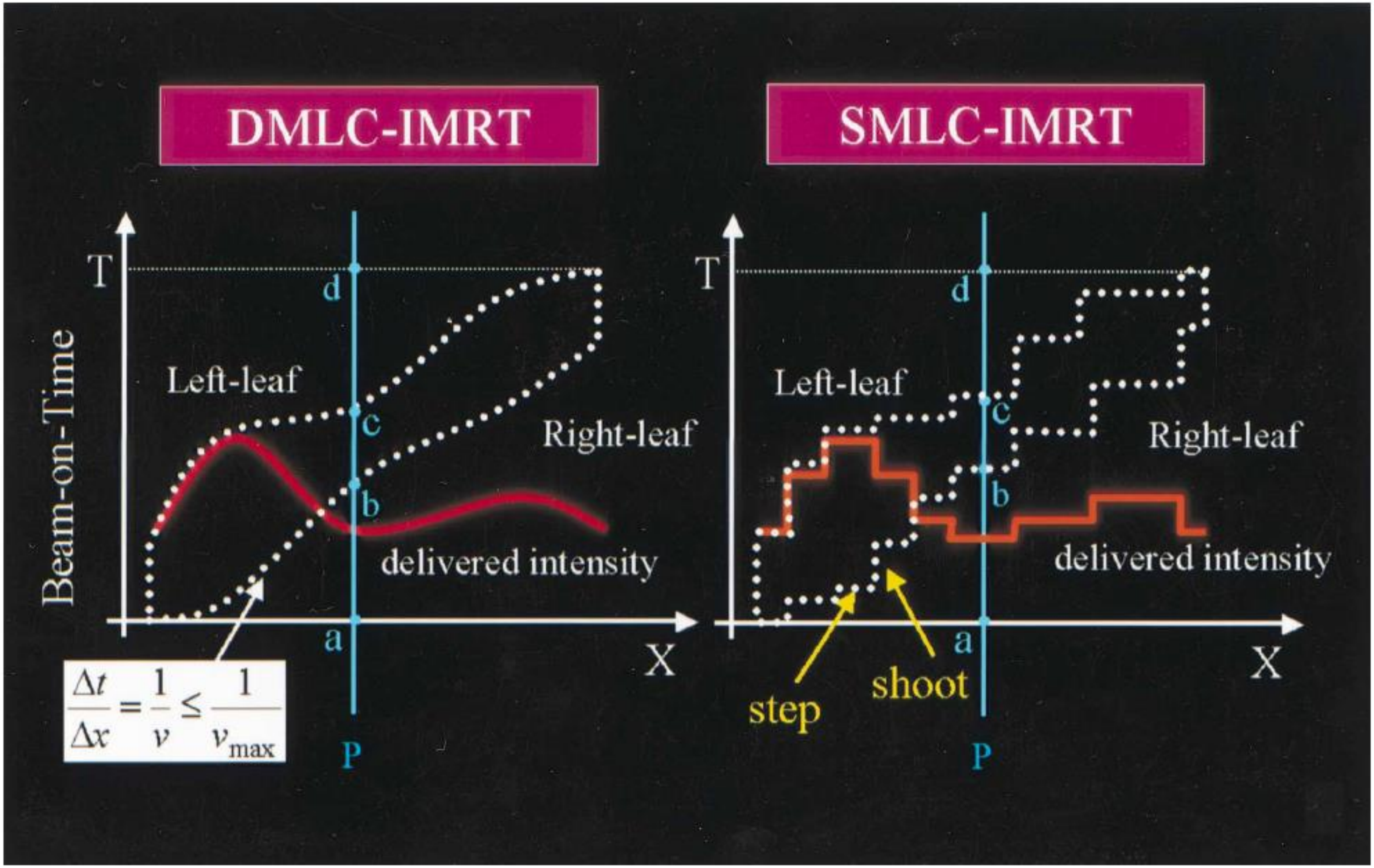


Fig. 6. (A) Intensity profile delivered by the leaves' paths of Fig. 5 (replotted here as dotted lines). In practice, a "leaf-sequencing" algorithm is used to translate the desired intensity profiles into a computer data file of the leaf positions as a function of MUs. (B) SMLC technique of delivering 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.

Int. J. Radiation Oncology Biol. Phys., Vol. 51, No. 4, pp. 880–914, 2001

Direct Machine Parameter Optimization

- Machine parameters (MLC position per control point) are optimized *directly* (rather than optimizing fluence)
  - Advantages:
    - avoids degradation of plan quality in converting optimal fluence to a leaf sequence
  - Disadvantages:
    - more difficult optimization problem
      - greater degree of non-linearity & parameter coupling
      - numerous linear constraints (machine limitations)
    - may require longer time required for optimization
    - needs good “starting point” for optimization

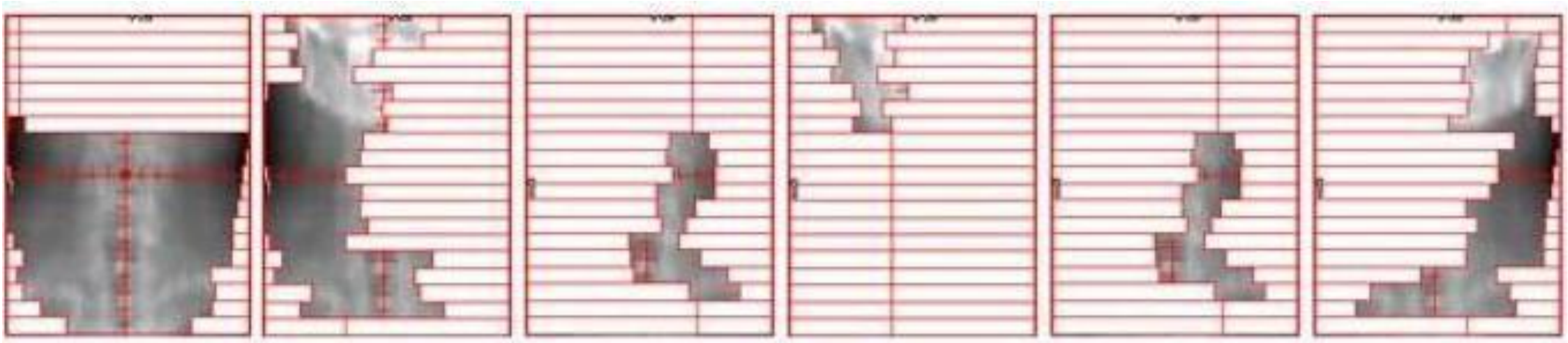
Direct Machine Parameter Optimization

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

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

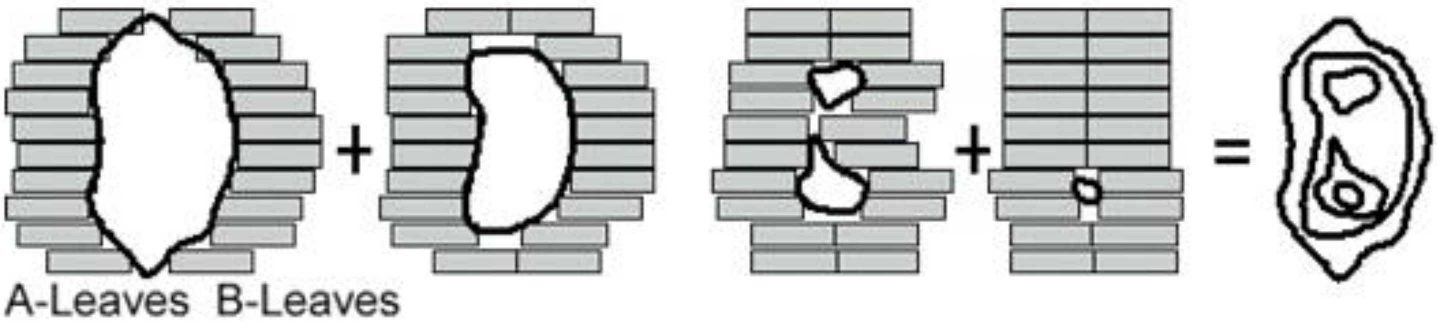


Figure 10.8: The basic idea of the step and shoot approach is to deliver an intensity modulated beam as a superposition of a set of irregularly shaped, partially overlapping field components

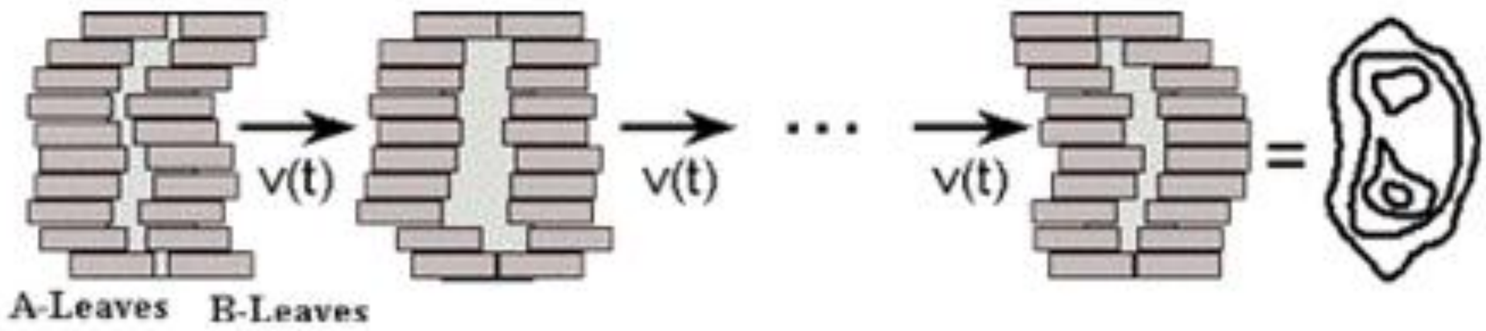
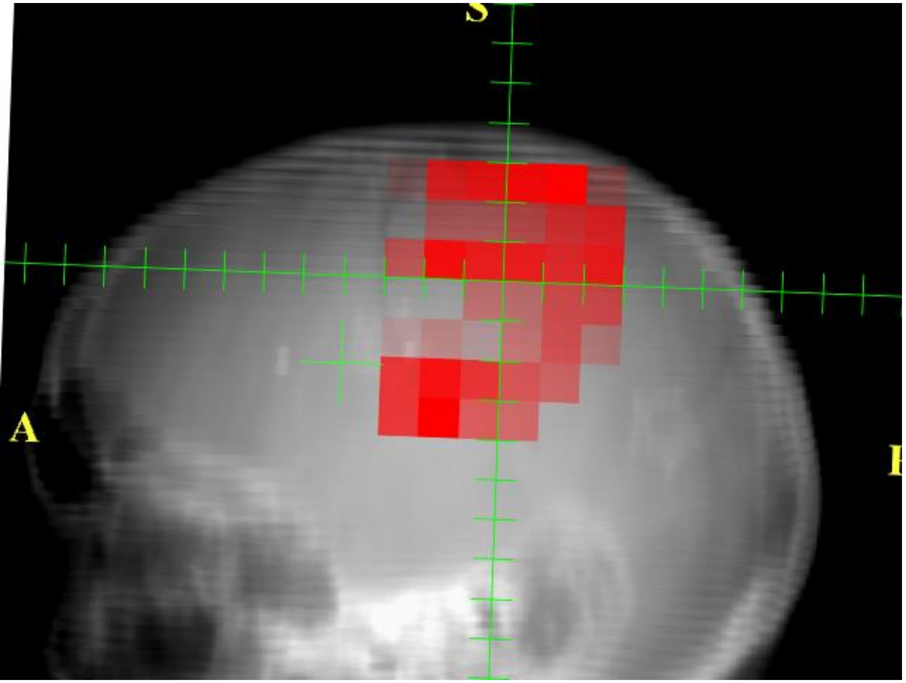


Figure 10.9: Principle of dynamic multi leaf collimation



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

Thank You!