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
- Sliding Window
- VMAT
IMRT Delivery: Step and Shoot
IMRT Delivery: Sliding Window
IMRT Delivery : VMAT
Motivation?
Motivation

3D conformal Rx

Intensity Modulation

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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
Forward Planning

- Treated Volume
- Target Volume
- OAR
- Collimator

Inverse Planning

- Treated Volume
- Target Volume
- OAR

Thomas Bortfeld et al.
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)
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

- Beam angles are set.
- Prescription is defined.

- Plan optimization is performed.
- A final dose calculation is performed.

O.K?  

- yes
- no

Approve plan for delivery.
The Beamlet Two-Steps Model

- 1st Generation IMRT was adopted by nearly all TPS in 1990:
  - 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

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

Not allowed

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.
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

- 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 2008-2015

- 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 $24^\circ$ 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.
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.
N and n Optimization: An Intermediate Case

Comparison of Dose Conversion Iteration
Case #6: 5235 Parameters

MU as Function of Conversion Iterations
Case # 6: 5235 Parameters
HN cases