Treatment Planning
3-D CRT to IMRT

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Aim

Introduce the techniques and possibilities offered by IMRT
Specific Learning Objectives

- Differentiate between inverse and forward planning
- Describe the concept of an objective function
- Describe the concepts of objectives, constraints and “weights”
- Set appropriate dose objectives
- Identify the need for additional planning volumes
- Compare dose based planning with biologically based planning
- Identify problems associated with IMRT planning
- Consider the possibilities for non-uniform dose distributions
  - Simultaneous integrated boost, nodal volumes
- VMAT
Outline of lecture

• What is IMRT
  • Forward Planned IMRT

Inverse Planning
  • Adding Structures
  • Adding beams
  • Objectives and Cost Functions
  • Setting Objectives
  • Optimisation
  • Creating deliverable fluences (Sequencing)
**Conventional RT**
Uniform intensity across radiation beam, Square or rectangular field

**3D-CRT**
Uniform intensity across the fields Irregular shapes of field

**IMRT**
Varying intensity of beam Irregular shapes & Higher conformity

**IGRT**
IMRT which changes as per change in size, shape and location of tumour and other organs

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**Pre-IMRT**  →  **IMRT dose sculpting**  →  **IMRT + IGRT dose sculpting + targeting**

- Improved outcomes
- Reduced side effects

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Sketch illustrating intensity modulated beams of radiation.
Benefits of IMRT

IMRT can be used to:

• Improve dose conformity to the target volume
• Produce concave treatment volumes
• Reduce dose inhomogeneities in off-axis slices
  – Compensating for surface shape
  – Compensating for tissue inhomogeneities
• Create deliberately non-uniform dose distributions
  – Concurrent boost treatments for prostate
  – Different doses to neck nodes
• Conformal Radiotherapy (CFRT) uses Multileaf Collimators (MLCs) to conform radiation beams to the shape of the target

• MLCs can also be used to create many small beams (or "segments") from each beam direction. This is called Intensity Modulated Radiotherapy (IMRT)
IMRT fields

- Divided into smaller elements called beamlets
- Size of beamlets is 0.25 cm in the x-direction and 0.5 in the y-direction (1.0 cm outer pairs)
- Ability to deliver many beamlets of varying radiation intensity within one treatment field
- Beamlet: Small element to be modified

0 = low intensity i.e., no dose will be delivered through this beamlet
1 = high intensity i.e., dose will be delivered through this beamlet
Forward and Inverse Planning

• **Forward Planning**
  - Dose, volume to be treated and avoidance structures defined
  - Beam directions defined
  - Dose calculated
  - Beam weights and wedges adjusted iteratively by the operator for an optimum plan
    • Beam directions adjusted manually if needed

• **Inverse Planning**
  - Dose, volume to be treated and avoidance structures defined
  - Beam directions defined
  - Objectives defined
  - Computer optimises beam weights and shapes to meet objectives
    • **Objectives adjusted** if plan unsatisfactory
Forward Planned IMRT

• Suitable for reducing 3D dose inhomogeneities and concurrent boosts

• Makes use of tools that are available in commercial treatment planning systems which help design modulated beams

• Because fewer beam segments are used QA is simpler
Dose hot spots with glancing fields to the breast using wedges.
Segment with skin surface shielded by MLCs

Beams Eye View showing medial tangent and a segment

Whole Breast PTV in lilac  Quadrant PTV in red
Hot spots reduced with segmented fields
Transverse Slice

Sagittal Slice

Prescription point

Isocentre

100% = red
95% = green
Simultaneous Boost for Prostate

High Dose area

Lower dose area
SCIENTIFIC NOTE

Can field-in-field technique replace wedge filter in radiotherapy treatment planning: a comparative analysis in various treatment sites

R. Prabhakar, P. K. Julka and G.K. Rath

Figure 1. Beam’s eye view of a field in field plan for a typical tangential field breast planning. Isodose surface >105% for an open field is shielded with MLCs. Cyan = 115-120%, dark green = 110 – 114.9%, light green = 105-109.9%, yellow=100-104.9%.
Inverse Planning

IMRT planning process

- Immobilization
- Imaging
- Structure definition (contouring target volumes, OAR)
- Treatment Planning
- Pre-treatment verification
- Treatment delivery

Beams definition (No. of beams, angle, energy) / Selection of class solution

Set dose contraints, penalties / priority

Run Optimization (Iterative process, tries to achieve dose constraints, generates fluence)

Select segmentation method

Dose calculation

Plan Evaluation

- Acceptable
- No

Adjust dose constraints / penalties
Inverse Planned IMRT

All tissues of interest must be outlined

PTV, OAR, BODY
Définition of Additional "Planning" Structures

• The optimiser will be confused if a voxel has opposing objectives
  – Subtract target volumes from OARs
  – Define parts of target where a dose limit is required
PTV subtracted from Bladder Volume

No hot spots are allowed in the Rectum part of the PTV
Overlapping structures

• Overlapping region with competing dose objectives
• Assign overlap region to new structure
• Assign distinct dose objective to each structure
Need to consider overlapping regions

Courtesy of Philips Medical Systems
Definition of Additional "Planning" Structures

• If a non-target voxel does not have a dose limit the optimiser may assign a high dose
  – Create ring structures around target tissues
Ring created around PTVs to avoid hot spots outside PTV

High Dose PTV

Prophylactic nodal irradiation

High dose overlap region
Planning organs at Risk volume

- ICRU 62 - recommend PRV
  - Changes due to organ motion & setup error during the whole course of Rx
  - Includes dose in the region in space where OAR is likely to be located

- PRV margin varies between centre to centre
- No consistency in its definition
  - Lack of clinical supporting data

PTV

PRV

Spinal Cord
Ring created around spinal cord to allow for setup inaccuracy to a very sensitive OAR.
A study on planning organ at risk volume for the rectum using cone beam computed tomography in the treatment of prostate cancer


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Choice of Beam Direction

• 9, 7 and 5 beams have been used in coplanar plans
• Plans do not have to be coplanar
• Appropriate choice of beam direction can be very effective
• Some systems now allow beam angle optimisation
• Increasingly arc therapy with dynamic jaw movements is being used.
Beam Angle Optimization
Optimization

• There is no exact solution to inverse problem
• Use objective function and employ optimization methods
• Optimization algorithms
  – Examples
    • Gradient decent
    • Simulated annealing
Pareto Optimization

- **Pareto optimality**, is a state of allocation of resources in which it is impossible to make any one individual better off without making at least one individual worse off.

- we cannot improve one parameter (e.g., reduce the dose in one OAR) without compromising at least one other parameter (e.g., reduce the target dose)
Setting the objectives
Mutlicriteria Optimization

Minimize \( \{f_1(x), \ldots, f_n(x)\}^T \)
where \( f_i(x) = i^{th} \) objective function to be minimized,
\( n = \) number of objectives

Subject to:
\( g(x) \leq 0; \)
\( h(x) = 0; \)
\( x_{\min} \leq (x) \leq (x_{\max}) \)

• If \( d_i \) is the actual dose and \( p_i \) is the prescribed dose, then the objective function \( F(x) \) can be expressed as

• \( F(x) = \sum_i (d_i - p_i) \) where \( d_i = f(x_1, x_2, \ldots, x_n) \)
and the DVH constraints are expressed as
  – \( d_i < d_{tol} \quad x_i > 0 \)
    where \( x = (x_1, x_2, \ldots, x_n) \) and \( d_{tol} \) is the tolerance dose.

The goal of the optimization process is to minimize the objective function \( F(x) \)
Cost Function

\[
C = \sum_{\text{objectives}} \sum_{\text{voxels}} W_i I_i (O_i - D_{\text{objectives}})
\]

W is the weight to allow more importance to be given to particular objectives

I=0 if the objective is met and =1 otherwise

A normalisation is applied so that ROIs with large numbers of voxels do not dominate

In order to carry out the optimisation the computer needs a function to optimise – this is called a “cost function”
Optimization in Eclipse

- All contours are sampled by point clouds
Biological Objectives are also possible

Dose-based IMRT Plan

Biological IMRT Plan

brain stem

Courtesy of Philips Medical Systems
### Structures and Objectives

<table>
<thead>
<tr>
<th>Structure</th>
<th>Volume [cc]</th>
<th>Points</th>
<th>Dose [Gy]</th>
<th>Resolution [mm]</th>
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<td>4211</td>
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<td>Overlap</td>
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<td>2478</td>
<td>70.0</td>
<td>1.69</td>
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<td>Post 1/3 Rect</td>
<td>11</td>
<td>2600</td>
<td>70.0</td>
<td>1.70</td>
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<td>PTV (LIM)</td>
<td>227</td>
<td>75.75</td>
<td>35.0</td>
<td>2.00</td>
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<td>Rectum (intra)</td>
<td>55</td>
<td>2160</td>
<td>70.0</td>
<td>2.05</td>
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### Base dose plan:
- Max time (min): 100
- Max iterations: 1000

### Automate optimization
- Automatic optimization process
- Automatic intermediate dose
A lower priority will appear as a right hand arrow that dose must exceed while an upper priority will appear as a left hand arrow that dose must not exceed
Parotids (parallel organ) have a mean dose tolerance so use multiple upper constraints to shape the DVH.

Brainstem (serial organ) has a point dose tolerance so use one upper constraint for 0% of the volume to go over.
Smoothening Objectives

• X-smooth
  – Helps the MLC deliver smooth fluences better and removes high frequency noise in the fluence
  – Has high impact on the Mus in the plan

• Y-smooth
  – Helps to minimize the tongue and groove effect
  – Higher the value, the more the smoothing is applied

If smoothing is too high it will affect the dose distribution and possibly sacrifice peripheral target coverage and give more dose to critical structures
All structures together is too busy

Hiding structures allows focus on individual structures

Constraint may be repositioned at any time by clicking and dragging within the interactive DVH
Red: NTO, Yellow: Structures, Green: Fields, Blue: DVH Purple: Progress Bar
NTO
a graph whose Y axis is %dose and X axis is distance from target border

A distance from target border is required to determine when the NTO will come into effect
Exclude every structure that won’t be used for optimizing
Conversion of Fluence Maps to Deliverable Beams

- Some optimisers calculate the optimum beam fluence but this is not deliverable.
- The ideal fluence is input to the Sequencer.
  - The Sequencer aims to produce the best match to the beam fluence with a minimum of segments.
- Step and shoot sequencers often produce different results.
- Dynamic sequencer more standardised.
- Needs to be adapted for linac.
  - E.g. when leaves will not close.
Leaf sequencing

1 1 1
3 2 3
2 2 1

1 1 1
1 1 1
1 1 1

0 0 0
0 0 0
1 1 0

0 0 0
2 0 2
0 0 0

0.5 1 1.5 2 2.5 3

0.5 1 1.5 2 2.5 3

0.5 1 1.5 2 2.5 3

0.5 1 1.5 2 2.5 3
Incorporating Sequencer into Optimisation
Effect of Sequencer

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<td>351</td>
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<tr>
<td>DMPO 35</td>
<td>35</td>
<td>374</td>
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<tr>
<td>IM 7.4</td>
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<td>428</td>
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<td>Plato</td>
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<td>512</td>
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<td>IM 6.2</td>
<td>63</td>
<td>546</td>
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<td><strong>Head and Neck</strong></td>
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<tr>
<td>DMPO 70</td>
<td>70</td>
<td>1026</td>
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<tr>
<td>IM 7.4</td>
<td>121</td>
<td>1213</td>
</tr>
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</table>
Fluence Maps

- Blue areas indicate the areas of least dose/intensity whilst red areas indicate maximum dose/intensity.
- Ensure that each fluence map has a graduated build up of blue, green, yellow, orange, red.

![Optimal Fluence Map](image1.png)

![Too Intense on Field Edge](image2.png)
Fluence Maps

• Any small isolated intense areas of red likely indicate an issue, possibly caused by:
  
  • Not enough margin on field edge
  • Shielding part of PTV in neck
  • The RT_PTV is too close to patient surface
  • Structures overlapping
Appropriate MLC – All PTVs Avoided

Inappropriate MLC – PTV Shielded

Appropriate Fluence – Even Dose Build Up

Inappropriate Fluence – Attempting to compensate for Neck Shielding PTV
Dose streaking around parotid – priority too high

Obl 130 Fluence – too intense around parotid = streaking

Post 180 Fluence – too intense around parotid = streaking

Obl 30 Fluence – too intense around parotid = streaking
H&N IMRT

Ideally the total number of MU’s should be <1200 for a bi-lateral technique and <1000 for a uni-lateral technique.

If the MU exceeds these values, assess each field individually. If all fields are contributing evenly it may just be a complex volume and appropriate. If one field is contributing disproportionately to the others, investigate further.

Fluence is too intense (0.542) leading to excessive MU (232). Field size needs to be increased or parotid constraints reduced.
Optimal fluence. Good build up to high intensity region.
Acceptable MU and acceptable intensity level.
PTV coverage

- Figure 1 shows small areas were 95% isn’t covering the PTV (cyan). The PTV copy (dark blue), is stretched in this area.
- Figure 2 post re-optimisation shows how the coverage is now achieved.
- Note: If coverage is skimpy in the Sup/Inf, the PTV copy can be added one slice above or below to achieve this also. However newer practice discourages this if D98% is achieved and suggest further rectal sparing instead.

Figure 1

Figure 2
Fluences

- Fluence maps need to be reviewed and ideally should all be under 0.4 for intensity.
- Figure below shows a typical fluence of a lateral beam, showing a high intensity region along the posterior PTV / anterior rectum, which is the most challenging area to deposit dose.
- Try to avoid any isolated intense areas and eradicated if possible. If it occurs on the beam edge, possibly increasing the field size may help. Otherwise reducing constraints in that region may also help.
Dose Dumping

- When working rectal constraints hard, it is very common to start seeing dumping in the outside the PTV
- Simple solution: Contour a dose control volume (DCV) around the dose dumping region, and place an upper constraint that is lower than the dose your trying to remove
- Example below, to remove the 50Gy hot spot, an upper constraint was give as 0% of the volume is to receive 49Gy with a modest priority of 60
Hot Spots

- Hot spots allowed inside the CTV but not outside the PTV
- If this occurs, use a dose control volume to contour out the problem area
- assign an upper objective that is lower than the one that lies in the problem area.
Cold spots

- Ideal – Uniform prescription dose to PTV
- If there is an even distribution of cold spots throughout, then it may be worth increasing the lower constraint of your PTV
- Few cold spots and you don’t want to make the whole PTV hotter, you can target this area with a dose control volume
- Simply contour the cold spot and place a lower objective that is higher than the one encompassed in the target area.
Overlap region of 4cm. Two centimetres either side of the isocentre
Beware high skin doses
Evaluating the final plan

• Good conformity
• Steep gradients around the OAR
• Hot volumes distributed around the PTV
• High dose volumes can occur outside the PTV
• More beams result in a low dose bath to the body outside the PTV
• Assess the plan using both the DVH’s and the dose distributions on all the slices
In Summary

• Appropriate outlining is vital
• Clear clinical specifications are essential
• Know your planning system’s algorithm
• Develop class solutions for consistency
• Collaborate with colleagues
Should we be doing IMRT?

- IMRT can be seen as an extension of 3D Conformal Therapy which is more demanding
  - Expertise in 3D conformal therapy is a prerequisite
- IMRT has been shown to be of benefit in a number of sites in reducing side effects
- Patients are increasingly expecting IMRT to be available to them
- IMRT is more expensive than conventional therapy – depending on how it is approached
Where is IMRT useful

- **Prostate**
  - Can minimise rectal dose

- **Head and Neck**
  - Simplifies treatment
  - Possibility of Parotid Sparing

- **Brain**

- **Spinal irradiation compensation**

- **Breast compensation**
  - Simple forward planned
  - Internal Mammary Chain treatment – full IMRT

- **Mesothelioma**
Cycle of IMRT introduction

• Commissioning
  – Design of IMRT technique
  – Setup of linear accelerators

• First patients
  – At least 10

• Treatment becomes routine

• Start another site
The Team

• Clinicians

• Planning
  – Physicists, Radiation Technologists (Radiographers), Dosimetrists

• Quality Control
  – Physicists, Dosimetrists

• Treatment
  – Radiation Technologists
Getting started

• Form a team
  – Physicists, Radiation Technologists, Doctors
  – Requires adequate staffing
• Understand the differences
• Decide on a site to start with
  – Head and neck gives most benefit
  – Prostate is simpler
• Develop class solution and compare to 3D CRT
• Make phantom measurements
Final Points

• For each site to be treated a detailed protocol is needed
  – Contouring guidelines
  – Additional planning contours
  – Clinical objectives
  – Starting point for planning objectives
  – Evaluation criteria

• General principles can be learnt on a course but most training needs to be related to the equipment to be used
Supplementary slides on Arc Therapy
What is VMAT?

• Volumetric arc therapy that delivers a 3D dose distribution.
• Inverse Planning Technique
• Delivered in a single arc or multiple arcs of angle up to 360°

• Simultaneously changes 3 parameters
  Gantry rotation speed
  Delivery dose rate
  Movement of MLCs
Animation of variable dose delivered to individual segments.
VMAT

- Varying dose per degree
  - Changing dose rate and gantry angle
- Dynamic MLC
  - MLC leaf are allowed to travel in and out
  - Leaf interdigitization

- ARC divided into simple segments defined by control points
- Each control point specifies the gantry angle, cumulative fractional MU and MLC leaf positions
VMAT

- Maximum 177 control points
- 1 segment every # 2 degrees for a full turn
  - (A control point every 2 degree of gantry angle)
- For each segment
  - Dose rate is constant
  - Gantry speed is constant
  - Starting and ending of MLC leaves are known
- Gantry, MLC and MUs are monitored every 50 ms
- Dose rate and gantry speed are adjusted if needed
Gantry speed & Dose rate modulation

- Gantry speed: 0.5 – 4.8 deg/sec (Variable)
- Dose Rate – 0 to 600 MU/min
- Dose/gantry rotation: 0.2 – 20 MU/degree
- MLC speed: 0 – 2.5 cm/s

- Gantry speed slow down to catch up the
- MLC leaf position
- Txt. depend on plan complexity
- To deliver max. dose /degree – GR↓, DR↑
Advantages compared to Fixed Field IMRT

• Shorter Treatment Times
  – Improves patient comfort
  – Limits unwanted patient movement
  – Decreases target motion

• Possibly better dose conformity and tissue sparing
## IMRT vs VMAT

<table>
<thead>
<tr>
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<th>IMRT</th>
<th>VMAT</th>
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<tbody>
<tr>
<td><strong>Gantry</strong></td>
<td>Static Gantry angle</td>
<td>Gantry rotating during treatment</td>
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<tr>
<td><strong>Dose Rate</strong></td>
<td>Fixed dose rate (usually)</td>
<td>Varying dose rate (Continuous variable dose rate)</td>
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<tr>
<td><strong>MLC speed</strong></td>
<td>MLC speed (constant)</td>
<td>MLC speed changes</td>
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<tr>
<td><strong>Plan Optimization time</strong></td>
<td>Less optimization time</td>
<td>More compared to IMRT</td>
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<tr>
<td><strong>Treatment time</strong></td>
<td>takes between 10 – 45 min</td>
<td>Short treatment time – bet. 1 min – 5 min (depends on the no. of arcs)</td>
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<tr>
<td></td>
<td>Prostate: 7 min</td>
<td>Prostate: 100 secs</td>
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Delivery of VMAT

• A Varian RapidArc™ plan is constructed as a sequence of 177 control points

• Each control point specifies the gantry angle, cumulative fractional MU and MLC positions
**VMAT**

**Dose Prescription**

<table>
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<th>Field ID</th>
<th>Technique</th>
<th>Machine/Energy</th>
<th>MLC</th>
<th>Field Weight</th>
<th>Scale</th>
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<th>Coll Rm (deg)</th>
<th>Couch Rm (deg)</th>
<th>Wedge</th>
<th>Field X (cm)</th>
<th>X1 (cm)</th>
<th>X2 (cm)</th>
<th>Y1 (cm)</th>
<th>Y2 (cm)</th>
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<th>Y (cm)</th>
<th>Z (cm)</th>
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<th>MU</th>
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**VMAT**

**Dose Statistics**

- **MU**: 620.807
- 23% less MU with VMAT
VMAT vs IMRT
Case 2: VMAT vs IMRT plans

**VMAT**  Total MUs: 737 MU

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**IMRT**  Total MUs: 1088

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% Reduction in treatment time with VMAT ~32%