Treatment Planning 2-D RT to 3-D CRT
The objective of this lecture is to integrate our knowledge of the differences between 2D and 3D planning and apply the same to various clinical sites. The final aim will be to be able to make out these differences and apply this knowledge to the clinic, critically analyse the plans generated and apply this in day to day selection of plans for treatment.
Specific Learning Objectives

- Differentiate between 2D and 3D plans
- Differentiate between 2D and 3D dose calculations
- Recognise the need for tissue homogeneity corrections
- Understand concepts of 3D planning
- Demonstrate these differences using clinical cases
- Analyse the differences between these plans
- Critical appraisal of the plans generated
The differences in the workflow during these forms of planning are shown in this and the following 2 tables. The table also highlights the differences and similarities in these 2 processes. It also presents the more intensive nature of the 3D planning process. It points out the steps where further resources need to be invested while moving to 3D planning.

<table>
<thead>
<tr>
<th>Key Steps</th>
<th>Typical Procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2DRT</td>
</tr>
<tr>
<td>Patient assessment &amp; decision to</td>
<td>• Clinical procedures</td>
</tr>
<tr>
<td>treat with curative radiation</td>
<td></td>
</tr>
<tr>
<td>therapy</td>
<td></td>
</tr>
<tr>
<td>Patient positioning &amp; Immobilization</td>
<td>• Establish treatment position</td>
</tr>
<tr>
<td></td>
<td>• Construct patient immobilization device</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Image acquisition</td>
<td>• Fluoroscopy</td>
</tr>
<tr>
<td></td>
<td>• Single CT slice in treatment position</td>
</tr>
<tr>
<td>Target &amp; organ contouring</td>
<td>• Concept non-existant</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Dose prescription</td>
<td>• Prescription in midplane or at isocentre</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## 2DRT vs 3-D CRT Workflow

<table>
<thead>
<tr>
<th>Key Steps</th>
<th>Typical Procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>2DRT</strong></td>
</tr>
<tr>
<td>Beam design &amp; arrangement</td>
<td>• Regular fields/ blocks</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Dose calculation</td>
<td>• Fill in the blanks</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan evaluation and</td>
<td>• Usually in a single plane</td>
</tr>
<tr>
<td>optimization</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# 2DRT vs 3-D CRT Workflow

<table>
<thead>
<tr>
<th>Key Steps</th>
<th>Typical Procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plan approval</strong></td>
<td>• Based on a single slice</td>
</tr>
<tr>
<td></td>
<td>• Perform overall review of all aspects of plan</td>
</tr>
<tr>
<td></td>
<td>• Plan approval by Oncologist</td>
</tr>
<tr>
<td></td>
<td>• Generate hardcopy output</td>
</tr>
<tr>
<td><strong>Generation of QA data</strong></td>
<td>• Weekly chart reviews/ at best weekly port films</td>
</tr>
<tr>
<td></td>
<td>• Generate DRRs for QA</td>
</tr>
<tr>
<td></td>
<td>• Generate of phantom plan for QA</td>
</tr>
<tr>
<td><strong>Treatment data file transfer to treatment machine</strong></td>
<td>• Manually</td>
</tr>
<tr>
<td></td>
<td>• Upload treatment parameters to record and verify system</td>
</tr>
<tr>
<td></td>
<td>• Verify transferred treatment parameters to treatment machine</td>
</tr>
<tr>
<td></td>
<td>• Verification simulation</td>
</tr>
<tr>
<td><strong>Treatment simulation</strong></td>
<td>• Conventional simulator</td>
</tr>
<tr>
<td></td>
<td>• Simulate &amp; verify the treatment plan</td>
</tr>
<tr>
<td><strong>Treatment delivery</strong></td>
<td>• Treatment delivery</td>
</tr>
<tr>
<td></td>
<td>• Field portal verification &amp; other QA checks</td>
</tr>
<tr>
<td></td>
<td>• Treatment delivery</td>
</tr>
<tr>
<td></td>
<td>• In vivo dose monitoring</td>
</tr>
</tbody>
</table>
This slide summarizes the entire 3D work process, from immobilization to delivery. The subsequent slides illustrate the similarities and differences in the entire process and also highlights certain features that maybe specific to a particular site.
Head & Neck

- Examine the clinical example: Case History, Imaging modality, staging
- Evaluate and critically appraise the plans generated:
  Use various physical and radiobiological considerations to differentiate between the plans
- Choose and recommend the optimum/best plan

The subsequent slides will follow a similar format, the case with a short clinical background, imaging information that aids in ascertaining the exact extent of disease, the choice of immobilization, the imaging for planning, contouring: primary and nodal basins, OARs specific to every site, deciding on planning objectives in terms of the target coverage and OAR doses, the 2 plans generated, the differences between the plans in terms of coverage of the target, doses to the OARS, analysis of the DVH. These will illustrate the differences between the two processes.
The Case:

Patient:
61 Year old female. R/O W.B. No h/o tobacco use, No co morbidity.

History:
P/W bleeding from mouth since 1-2 months in August 2006

Clinical Examination:
An ulceroproliferative 2 X 1 cm growth on Rt. BOT reaching vallecula. Not crossing midline. No palpable neck nodes.

Biopsy:
Squamous cell carcinoma

Routine investigations and distant metastatic work up:
All normal

Imaging findings:
PET CT (7.09.06): Focal area of increased uptake (max SUV 13.8) in Rt Tonsillar region, Tonsillo lingual sulcus & adjacent BOT. B/L neck showing small nodes with minimal increased uptake.

Diagnosis:
Ca Rt BOT SCC cT2 N0 M0
Contours

- The concept was absent/ except for perhaps a single slice in 2D
- Treatment decided on dose distributions seen at a dingle slice, plane
- Concept of volume missing
2-D Planning

- Simulation
  - Orthogonal films

- Manual contour of the breast
- Single slice 2-D planning

W Beckham
Patient Data Acquisition and Simulation

- Patient information required for treatment planning depends on type of system used

2-D

3-D

ICRU 50
### Diagnosis: Ca Rt BOT SCC cT2 N0 M0

<table>
<thead>
<tr>
<th>Name of The Volume</th>
<th>Contoured Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTV_Pr</td>
<td>Gross disease</td>
</tr>
<tr>
<td>CTV_66/30</td>
<td>GTV_Pr + 0.5 cm</td>
</tr>
<tr>
<td>PTV_66/30</td>
<td>CTV_66/30 + 0.7 cm</td>
</tr>
<tr>
<td>CTV_60/30</td>
<td>Right level II</td>
</tr>
<tr>
<td>PTV_60/30</td>
<td>CTV_60/30 + 0.7 cm</td>
</tr>
<tr>
<td>CTV_54/30</td>
<td>Right levels III – IV + Left level II</td>
</tr>
<tr>
<td>PTV_54/30</td>
<td>CTV_54/30 + 0.7 cm</td>
</tr>
<tr>
<td>To also include OARs and their dose objectives</td>
<td></td>
</tr>
</tbody>
</table>

The table talks about the various target volumes delineated on the CT slices for this case. It also highlights the ability to deliver different doses to different levels of neck nodes, thereby allowing better sparing of adjacent normal tissues.
Cranial most slice with only the CTV and PTV, and OARs like parotids, brainstem
More slices with the CTV and PTV, and OARs like parotids, spinal cord
Cranial most slice with only the CTV and PTV, and OARs like parotids, brainstem/spinal cord. In addition the GTV and nodal CTV also can be seen. What should also be appreciated is the PORV to the spinal cord. A concept almost non existent with 2D planning.

The PORV (Planning Organ at Risk Volume) is added for uncertainties and variations in the position of the OAR during treatment and must be considered to avoid serious complications. For this reason, margins have to be added to the OARs to compensate for these uncertainties and variations, using similar principles as for the PTV. This leads, in analogy with the PTV, to the concept of PRV.

Every CT slice must be contoured for the various volumes.
Note the difference between the CTV of involved nodes (R) versus uninvolved nodes (L)
The thickness of each CT slice partly depend on the site and tumour type.
The shape of all relevant contours changes with every slice.
Plan
Typical prescription for 2D planning

• Portal arrangement
• Field size
• Depth of prescription
• Use of treatment accessories
• Dose per fraction
• Treatment time/ Monitor unit calculation
• Port/ Simulation film
Treatment simulation with conventional simulator

Purpose:

1. For planning of treatment beams
2. To simulate & verify a treatment according to treatment plan using a conventional simulator
3. Generate the reference images with treatment isocentre and other anatomical markers for treatment verification and QA at treatment machine.

The above functions can be performed by a CT simulator which can serve as a planning CT scanner as well as a treatment simulator.
In 3D planning one of the key differences is the need for Beams Eye View (BEV) and Digitally Reconstructed Radiographs (DRR). These serve a similar function to port films and simulator films.
3D planning uses multiple conformal beams usually shaped with multi-leaf collimators (MLC) although it is possible to do beam shaping with customised blocks as well.

Compared to 2D planning, where co-planar set-up of 2-4 beams are used, 3D planning allows more treatment fields to be used either in a co-planar or non-coplanar set up. This may allow better sparing of OAR.
Non-coplanar fields are most often used in H&N and brain tumours where the target volume is surrounded by OAR.

With non-coplanar beams, it is essential to ensure collision does not occur with gantry head and couch / patient.
### Non-coplanar Beams

**Benefits**
- Exit dose is not superimposed on entrance dose
- Reduces impact of MLC leaf steps

**Potential problems**
- Requires accurate isocentre
  - Or appropriate compensation system
- Staff must enter the room between fields

---

Non-coplanar beam require repositioning of the couch and gantry movement to ensure accuracy of treatment.
The plans generated by either method are then compared for the various objectives set, the target volumes, OARs.

<table>
<thead>
<tr>
<th>Objectives</th>
<th>2DRT</th>
<th>3DRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target: Dmin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dmean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dmax</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OAR: Spinal Cord</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brainstem</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parotids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mandible</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• Comparative plans
With multiple beams in 3D planning, it is possible to simulate IMRT treatment. Here we can see that the dose is sculptured around the spinal cord.
Multiple field planning with 3D CRT yields a better dose distribution around the target volume. This allows sparing of OAR. In this example the parotid gland receive less than 33 Gy compared to 53-59 Gy with 2D planning.
The advantage of 3D CRT and multiple beam plans is even more obvious with complex shaped target. The contours for nasopharyngeal and pharyngeal cancers usually include the retropharyngeal nodes giving an inverted U contour. With multiple beams, it is possible to shape the isodoses to fit this contour and spare the spinal cord.

With 2D planning, the beam set up is compromised as to avoid spinal cord injury and therefore part of the target volume is underdosed.
• Comparative DVH
# DVH Summary

<table>
<thead>
<tr>
<th>Structure</th>
<th>Min Dose(%)</th>
<th>Max Dose(%)</th>
<th>Mean Dose(%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTV_66/30_Pr</td>
<td>81.7</td>
<td>104</td>
<td>99</td>
<td>95% PTV covered by 95% dose. Negligible dose &gt;105%</td>
</tr>
<tr>
<td>PRV Cord</td>
<td>0.5</td>
<td>66.9</td>
<td>32.3</td>
<td>2% cord receiving 60 Gy</td>
</tr>
<tr>
<td>Spinal Cord</td>
<td>0.5</td>
<td>60.7</td>
<td>32.9</td>
<td>2% cord receiving 58 Gy</td>
</tr>
<tr>
<td>Brain Stem</td>
<td>1.6</td>
<td>64.5</td>
<td>11.5</td>
<td>2% Brain stem receiving 57 Gy</td>
</tr>
<tr>
<td>Rt. Parotid</td>
<td>9.6</td>
<td>100.5</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>Left Parotid</td>
<td>6</td>
<td>84.3</td>
<td>39</td>
<td></td>
</tr>
</tbody>
</table>
2D Vs 3D

LUNG
Treatment planning for lung cancer has the usual problem of nearby OAR especially spinal cord. However there is the added problem of tissue inhomogeneity due to the low density of lung tissue.
Tissue Inhomogeneity Corrections

• Simple
  – Assume all tissues are water-equivalent

• Reality
  – In actual patient, photon beam traverses tissues with varying densities and atomic numbers
  – E.g., fat, muscle, lung, air, and bone.

• This influences attenuation and scatter of photon beam such that isodose curves will deviate from that in water

Inhomogeneity corrections accounts for different tissue densities and different attenuation by tissue.
This example shows the difference in isodose profile of a single field with and without inhomogeneity correction. With correction, the lung dose is higher than anticipated.
3-D Planning, Tissue Inhomogeneities

• With many TPSs (but not all), user can choose:
  – to ignore tissue inhomogeneities
  – to perform bulk corrections on outlined organs
  – to use the CT data itself (with conversion to relative electron density) for point-to-point (pixel-based) correction
With 2D planning all beams are generally place on the side of the “bad” lung. We can see on this plan that the spinal cord within all 3 fields as well as most of the heart.
Converting 2D planning with a 3D BEV, the problem is more evident.
Most of the 3 OARs are within the field of treatment.
Although it is possible to shield some parts of these organs in 2D planning, as the dosimetry is only on 1 (or few slices), it would not be possible to see the effect of shielding on the whole tumour volume. With conformal technique, the MLC is shaped around the target volume and/or away from OAR.
The next few slides show the improvement in dose distribution for 3D CRT.
V20

2D - 20Gy

3D - 20Gy

Volume of lung receiving 20Gy is more in 2D Plan
Distribution of 45 Gy

2D - 45Gy

3D - 20Gy

Volume of Normal tissues receiving 45Gy is more in 2D Plan
From the DVH of 2D vs 3D plans, there is marginal differences between the coverage of the TV. is increased in irradiated volumes of OAR. There is increased dose to OARs. The mean lung dose is increased by 10% (21% to 31%) and spinal cord dose by 20% with maximal dose of 106%. This indicates there is high risk for late spinal cord damage.
Superimposing the 2 plans, we can see that tumour coverage is similar and OARs receive higher doses. Note especially the DVH for spinal cord reaches 100%.
2D Vs 3D

Breast
In planning for breast cancer, there is less issues with OAR. However the shape of the target is more complex (it is not rounded) with a curved skin surface. The organs and targets are contoured in the usual manner.
2D planning is done by skin marks and then planned with conventional simulator. The OAR limit is usually the maximum amount of lung tissue within the field, usually less than 3cm.
The 2D BEV covers the superficial parts of the ipsilateral lung
3D Beam Orientation

Bi-tangential Fields but Reverse Planning
In 2D planning, the dose at the central slice may be adequate but we can see there are hotspots especially in the superior part at the axilla and also increase dose to the lung.
With 3D planning, the hotspot is still present but much less (109% vs 121%). The dose to the lung is also less.
Side by side we can appreciate the differences better
2D Vs 3D

Cervix
Cervical cancers may be planned with either 2 or 4 field technique in 2D planning. This is a typical anterior field film.
By contouring the TV, we can see there may be areas of inadequate coverage with conventional fields.
Simple AP/PA fields results in increased doses to the surface and subcutaneous tissue. The difference is more pronounced with larger patient separation and lower beam energies. There is also central “waisting” with reduced coverage in the centre which is where the tumour is.
Often there is also hotspots due to irregular patient contour anteriorly and smaller separation inferiorly. There is also a tendency for the superior region to be “colder” due to increased patient abdominal thickness.
The dose distribution for cervical cancer can be improved with the use of a 4-field box technique.
The dose distribution is better but there are still some hot spots anteriorly. (In this example, the inguinal nodes are contoured as part of PTV.)
Standard blocks can be used to shield off OAR namely the rectum and sacral nerve roots.
In 3D CRT, a 5 field co-planar set up can be used
This results in better dose distribution with less dose to OAR and smaller hotspots.
Dose Distribution – 3D
The high dose area is sculptured around the sacral hollow.
Dose Distribution – 3D
Conventional "2-D" Radiotherapy

Radiotherapy is a 3-D process

Before the 80's the planning & treatment processes were 2-D

Conventional radiotherapy/ 2-D planning: Single slice CT or a combination of patient contour and plan film radiography

Patients usually planned and treated as a uniform structure

There was little correction for tissue inhomogeneity especially small air cavities such as the nose.
Conventional 2-D Planning

- Patient represented by a single plane, i.e. the transverse plane containing the isocentre of the beams: No concept of volume
- Patient information acquired by manually digitizing the patient contour or contouring on a single CT slice
- Central axes of the treatment beams assumed to lie in the calculation (principle) plane
- Dose distributions calculated in this plane, assuming the patient cross section to be identical throughout the entire patient volume
- Patient regarded as a uniform structure and no inhomogeneity corrections made in dose calculation
- Treatment plan evaluated by examining the dose distribution only in plane of calculation
Limitations of 2-D Treatment Planning

• Unable to determine if adequate dose distribution can be delivered to cover the entire target volume.

• Unable to deliver satisfactory dose to complex shaped target.

• A large volume of normal tissue is irradiated to high dose.

• Dose to the critical structures, e.g. the brain stem, spinal cord and temporal lobes in head & neck treatment, cannot be evaluated properly.

Doses to OAR are often not in the central slice. Safety is estimated by judging the OAR is in or out of a field eg... is the eye in the field or exit dose?
Typical Problems with 2-D Treatment

- Some normal critical tissue structures are irradiated to high dose leading to:
  - treatment toxicity and complications
  - Restrictions on dose escalation or re-treatment
- Target under-dose leading to higher chance of recurrence.
Potential benefits of 3-D CRT

- Improvement in target dose conformity: Better delivery of prescribed doses, improved local controls
- Reduction of normal tissue irradiation: Minimize degree of treatment induced normal tissue complication, improvement in quality of life
- Facilitate the possibility of dose escalation: Improved local controls with no added toxicity
Potential Limitations of 3DRT

- Sophisticated treatment and planning procedures: Need appropriate technology and expertise
- Good understanding of cross-sectional anatomy and natural behaviour of disease: What is not contoured is not treated
- Need for stringent QA procedures to ensure accurate treatment planning and delivery
- More difficult to verify non-perpendicular beam arrangements
  - Usual anatomical landmarks are lost
Potential Limitations of 3DRT

- Higher integral dose: Higher probability of radiation induced secondary cancer in the irradiated volumes. Requires long term follow up to show the effect.
- Higher cost & staff time
  - Contouring of target and OAR
  - Planning and plan evaluation
  - QA
Summary

• 3-D CRT can potentially deliver a highly conformal radiation dose to the target and at the same time better protect the normal tissue structures.

• Dose escalation for better local control without causing treatment complications is possible.

• 3-D CRT is a high precision treatment and the procedures involved are complex.

• Treatment planning is based on 3-D volumetric image data

• Stringent QC measures in every step of 3-D CRT is important for proper and safe implementation of the technique

• Implementation of the treatment can be demanding on equipment facilities, manpower and expertise.