Physics associated with conformal radiation
- An overview

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The evolution of treatments

2D planning

3D planning

IMRT planning

Adaptive planning
The era of 2D Radiotherapy!

- Based on surface anatomy or x-rays
- Box fields
- Conformality achieved with putting custom made blocks and wedges
Move to 3D treatments: What all changes??

• Shift from bony landmarks to 3 dimensional structures for tumour volumes

- Imaging: CT/MRI/PET
- Registration: Rigid/Deformable
- Segmentation
- Planning and plan evaluation: - Multiple beams
- Beam angles
- Beam apertures; MLCs
- Beam weights
- Beam modifiers (wedges and compensators)
What doesn’t change?

Beam profile remains consistent
• In 2D radiation and 3DCRT, radiation beams are of uniform intensity across the field (within the flatness specification limits).

• Occasionally, wedges or compensators are used to modify the intensity profile to offset contour irregularities and/or produce more uniform composite dose distributions.

• This process of changing beam intensity profiles to meet the goals of a composite plan is called intensity modulation.
IMRT: Intensity modulation radiation therapy

• In IMRT, a non-uniform fluence is delivered to the patient from any given position of the treatment beam to optimize the composite dose distribution.

• The treatment criteria for plan optimization are specified by the planner and the optimal fluence profiles for a given set of beam directions are determined through “inverse planning”.

• The treatment planning program divides each beam into a large number of beamlets and determines optimum setting of their fluences or weights.
Treated Volume

Target Volume

Tumor

OAR
IMRT

- Physical modulator IMRT
- Conventional MLC IMRT
- Tomotherapy/helical IMRT
- Robotic Linacs

*ASTRO-AAPM Collaborative working group
Conventional MLC IMRT: 
--fixed gantry and rotating beams

**Fixed gantry angle IMRT**

- **Segmental delivery:**
  - stack arrangement of fixed uniform intensity sub fields
  - Accelerator turns off in between
  - Step and shoot
  - Leaves may sweep or close-in
  - Easy to operate but On and off accuracy may be an issue

- **Dynamic MLC delivery**
  - leaves sweep simultaneously and unidirectionally, each with a different velocity as a function of time
  - Accelerator beam is on while the leaves are moving
  - Sliding window IMRT
Rotating beams IMRT

✓ IMAT

✓ VMAT

- Gantry moves continuously, while MLC leaves and dose rate changes continuously
Tomotherapy/Helical IMRT

• The patient is treated slice by slice by IMBs in a manner analogous to CT imaging.

• A special collimator is designed to generate the IMBs as the gantry rotates around the longitudinal axis of the patient.
Tomotherapy Unit

A

B

Spiral Scan
IGRT: Image Guided Radiation Therapy

• Broadly, IGRT may be defined as a radiation therapy procedure that uses image guidance at various stages of its process: patient data acquisition, treatment planning, treatment simulation, patient setup, and target localization before and during treatment.

• In the present context, we will use the term IGRT to signify radiotherapy that uses image guidance procedures for target localization before and during treatment.

• A very important requisite given that we have very conformal dose distributions
IGRT

• Eventually most radiotherapy will be IMRT, even many palliative treatments, e.g., re-treatment

• All IMRT should be image-guided: – IMRT spares critical tissues (conformal avoidance), produces higher dose gradients.
  – IGRT enables higher gradients to be delivered safely and effectively.
  – IGRT enables a smaller setup margins to be defined.

• In some radiotherapy sites, e.g., prostate, IGRT is more relevant

• Afterall, equating it with surgery as a local therapy, we too need to see it and the treat it!!
2D systems - x rays

ELECTRONIC PORTAL IMAGING DEVICES

Portal images and radiographic images
  MV and KV imaging; KV imaging also enable fluoroscopy and MV enable online monitoring of target position

  2D imaging is inadequate to obtain volume information
CT in Treatment Room

CT in the Treatment Room “First CT then Treat”

Siemens CT vision: Primus Linac+diagnostic CT
“CT on Rails”

GE CT + Varian Linac
Cone Beam Imaging: KV

The on-board kV imaging system is capable of radiography, fluoroscopy, and cone-beam computed tomography (CBCT).

The CBCT involves acquiring planar projection images from multiple directions as the gantry is rotated through 180 degrees or more.
MV CBCT

• Possible with the existing EPID setting, no extra hardware required

• Less contrast as compared to better contrast with KV CBCT, hence poor soft tissue resolution

• No issues with artifacts: dental fillings, hip implants

• No need to extrapolate attenuation coefficients

• Imaging dose easily quantified as therapeutic beam dose known
So far so so good!
• There is internal movement and deformation in multiple organs with respiration

• Tumors in the lung, liver, pancreas, esophagus, breast, kidneys, prostate, and other neighboring sites are known to move due to respiration.

• AAPM TG 76 recommends considering respiratory management techniques if range of motion exceeds 5mm in lung tumours

• Thus, need for intra-fraction motion management techniques arises
Intra-fraction motion management

- 4D-CT
- Real time tumour tracking
- Electromagnetic field tracking, MR tracking
4D respiratory trace

Concept of ITV
Breath- hold treatment

Patients’ console respiratory trace image, Yellow colour indicates radiation beam on time
Real time tumour tracking

• It detects the respiratory motion and dynamically reposition the radiation beam in order to follow the tumor’s changing position.

• Because of the difficulty of detecting the tumor itself, surrogate markers (external fiducials on the skin surface or internal fiducials implanted directly into the tumor) are used in most cases.

• The time delay between the detection of motion and the corrective action should be short (on the order of 100 milliseconds)
Exactrac/Brainlab system

2 real time imaging systems
  • Optical system with Infra-red cameras
  • Fluoroscopic system (x ray tubes in floor and detectors in ceiling)
  • 6D couch
Cyberknife
Miscellaneous physics concepts: MLCs

Tertiary collimators: **Multi-leaf collimators**
• Leaves that can be driven automatically, independent of each other, to generate a field of any shape

• Typically consists of 60 to 80 pairs, independently driven. The individual leaf has a width of 1 cm or less as projected at the isocenter.

• The leaves are made of tungsten alloy & have thickness along the beam direction ranging from 6-7.5 cm. The leaf thickness is sufficient to provide primary x-ray transmission through the leaves of less than 2% (compared with about 1% for jaws and 3.5% for Cerrobend blocks). The interleaf (between sides) transmission is usually less than 3%. The primary beam transmission may be further minimized by combining jaws with the MLC in shielding areas outside the MLC field opening.

• Imp MLC QA- Stability of leaf speed, Dose profile across adjacent leaves, Leaf acceleration and deceleration, Positional accuracy of leaves, Routine mechanical check, Collimator transmission
Flattening Filter Free (FFF) beam

<table>
<thead>
<tr>
<th>Energy</th>
<th>PDD(10 cm)</th>
<th>SURFACE DOSE</th>
<th>Dmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>6MV FF</td>
<td>65.9</td>
<td>51.2</td>
<td>14.9</td>
</tr>
<tr>
<td>6MV FFF</td>
<td>63.6</td>
<td>58.99</td>
<td>12.95</td>
</tr>
<tr>
<td>10 MV FF</td>
<td>73.8</td>
<td>37.6</td>
<td>24.8</td>
</tr>
<tr>
<td>10MV FFF</td>
<td>71.13</td>
<td>43.01</td>
<td>23.0</td>
</tr>
</tbody>
</table>

Rule of thumb:
X6FFF ~ X4, X10FFF ~ X8
**TABLE 20.1** IMRT Quality Assurance Program

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Procedure</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before first treatment</td>
<td>Individual field verification, plan verification</td>
<td>3% (point dose), other per clinical significance</td>
</tr>
<tr>
<td>Daily</td>
<td>Dose to a test point in each IMRT field</td>
<td>3%</td>
</tr>
<tr>
<td>Weekly</td>
<td>Static field vs. sliding window field dose distribution as a function of gantry and collimator angles</td>
<td>3% in dose delivery</td>
</tr>
<tr>
<td>Annually</td>
<td>All commissioning procedures: stability of leaf speed, leaf acceleration and deceleration, multileaf collimator transmission, leaf positional accuracy, static field vs. sliding window field as a function of gantry and collimator angles, standard plan verification</td>
<td>3% in dose delivery, other per clinical significance</td>
</tr>
</tbody>
</table>
Be cautious!

More conformality we achieve, more confident we need to be of our
• Planning CT, Target delineation
• Motion management
• PTV and penumbra margins
MR-guided system

- Incorporating MR for simulation & treatment planning allows reproducible millimeter accuracy in soft tissue definition
- Functional imaging (DCE/DWI) allows dose painting to high risk tumor volume for greater tumor control
- MR OBI (on board imaging) allows target and critical structure localization & tracking based on gold-standard anatomy rather than fiducial markers, bony anatomy or other surrogate as in CT
- Intra-fraction anatomic and functional imaging allows early evaluation of tumor response and adaptive treatment escalation or de-escalation to improve tumor control or treatment toxicity
MRI-guided Radiotherapy: An Emerging Paradigm in Adaptive Radiation Oncology

- Online MRI-guided RT offers unprecedented opportunities for interfraction and real-time intrafraction adaptation to organ motion and calculation of dose accumulation.
- Using MRI in RT will improve the monitoring of tumor biology during radiation treatment and develop novel imaging biomarkers for assessing tumor response.
- Challenges to MRI-guided RT include real-time volumetric anatomic imaging, reproducible quantitative imaging across different MRI systems, and biologic validation of quantitative imaging.

Axial and coronal MRI scans show the interfraction motion of organs at risk (liver, bowel, kidney, stomach, and duodenum) in a patient with pancreas cancer undergoing stereotactic body radiation treatment on the 1.5-T MRI-guided linear accelerator.

Otazo R et al. Published Online: December 22, 2020
https://doi.org/10.1148/radiol.2020202747
PET/CT linac for biology-guided radiotherapy

- BgRT delivery uses annihilation photons emanating from the PET-avid tumor to guide the delivery of beamlets in real-time.
- BgRT treatment technique opens the avenue to debulking advanced and metastatic disease.

An overview of the BgRT system showing some of the major subcomponents.

Clinical workflow of BgRT system.
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