Intensity Modulated Radiation Therapy: Dosimetric Aspects & Commissioning Strategies

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Steps to Preparing for IMRT

1. Delivery System Commissioning
   1. Mechanical tasks
   2. Dosimetric tasks (3D)
   3. IMRT specific tasks

2. Treatment Planning System Commissioning
   1. 3D tasks (*IAEA Report TRS 430 (2004), ESTRO Booklet 7, Camargo 2007*)

3. Dosimetric verification per plan / site
4. Independent verification / credentialing
5. Pre-treatment verification (per plan)
Figure 3.1 (a) Conceptual pyramid that correlates the various levels of dosimetric QA in IMRT. Like the situation for a real pyramid, each level is based on the stability of the underlying levels. The two lower levels can be part of the periodic QA procedures of equipment used for IMRT planning and delivery. For QA of a new clinical IMRT solution, one may start at the top by applying a 3D dosimetric verification of an entire treatment. One descends the pyramid to the lower levels if the 3D dosimetric verification reveals unacceptable discrepancies with treatment planning. (b) Methodology and tools appropriate for each of the levels. (Courtesy Carlos De Wagter, Ghent University Hospital, Ghent, Belgium, and the Institute of Physics).
1. Delivery System Commissioning
IMRT Commissioning of Delivery System: General issues for IMRT using an MLC

- MLC Position Accuracy
  - Picket or Garden Fence / strip test
- Linac performance for small MU delivery
- MLC control issues & data transfer fidelity
- MLC physical (& dosimetric) characteristics
  - Dosimetric leaf gap (DLG)
  - Inter & Intra leaf leakage
  - Tongue & groove effect
- Additional issues specific to sliding window IMRT
  - Leaf position & leaf speed accuracy
  - Minimum leaf distance (to avoid collisions)
MLC Position Accuracy

• 3D: MLC defines field edge
  – 1-2mm offset may be inconsequential to output & clinical outcome

• IMRT:
  – Consists of multiple small “segments”
  – Leaf edge moves to many positions within the treated area
  – Hence IMRT accuracy is much more sensitive to MLC edge position

• Rounded leaves: 0.4-1.1mm offset between light field edge & beam edge
MLC Positional Accuracy: Proposed Test (AAPM Report 82):

- Proposed test procedure:
  - Measure offset between light field & radiation field as a function of distance from the central axis
    - often offset may be considered to be constant
  - Create test sequence that abuts irradiated strips at different locations across the field
    - account for offset so that 50% lines superimpose
  - Irradiate film & evaluate uniformity of dose
- Repeat at various gantry angles to assess effect of gravity
- Test over range of “carriage” motion for MLCs utilizing a carriage
Abutting MLC Dose Uniformity Test

expected detectability = 0.2mm ±5% dose accuracy in the matchline

Fig. II.1. (a) MLC test pattern with a 2 cm wide strip. (b) QA film produced by moving the pattern in 2 cm intervals and irradiating in a step-and-shoot fashion. The strips should abut at the 50% decrement lines as described in Sec. II A1. The line on the film shows the location of the scan (c), which is used to assess the quality of the matching. This MLC has a rounded leaf end design.
MLC Positional Accuracy: Picket Fence Test

- Test sequence that creates 1mm strips at regular intervals
- Visual inspection can detect improper positioning of ~0.5mm
- Repeat at multiple gantry & collimator angles
MLC Position Accuracy: Picket Fence Test

Figure 4.1 A strip-test design for MLC calibration purposes showing nine adjacent segments 2 cm wide with 1 mm gap, and two extra segments with 4 squares at the left and right side to determine the isocentre, measured with film. Dose profiles are taken for each leaf-pair. The right figure shows the profile of a central leaf. The dose variations of the abutments are used to determine the relative leaf positions, and the measured position of the abutments to determine the absolute leaf position (from Sastre-Padro et al., 2004).
Linac performance for small MU delivery

• Step & Shoot IMRT consists of multiple small segments with few MU - requiring accurate dose linearity at low MU

• Recommended to verify output, along with flatness & symmetry

Figure 4.6 Beam calibration for a limited number of monitor units depending on the type of magnetron and steering technique for Elekta accelerators. In 1997 the feedback technique with slits was used. An improvement of this technique was the slitless flight tube, which was followed by a new design magnetron with faster tuning (Courtesy Geoff Budgell, Christie Hospital, Manchester, UK).
MLC control issues

• Need to determine the following for specific equipment:
  – how MLC is calibrated
  – how MLC position is indexed to MU
  – how MLC position is measured
  – MLC tolerance applied (& can this be modified)
  – interlocks for MLC position
  – verification records & logs are created by the control system
  – how to respond when calibration has drifted
  – how to recover from delivery interruptions

• Vendor implementation of IMRT:
  – Segmental IMRT may be implemented as an extension of conventional treatment with each segment as a separate field (Siemens)
  – IMRT may utilize a dedicated linac & MLC control system (Elekta & Varian)
Data Transfer Fidelity

• Visual verification that plan data has been transferred correctly between TPS and linear accelerator for representative plans
  – straightforward for basic machine settings & initial MLC shapes

• MLC motion is less straightforward to verify
  – dosimetric measurements may be a good surrogate

• After commissioning: it is a good idea to have a policy in place to verify this on a per-plan basis
MLC physical (& dosimetric) characteristics

- **MLC leakage**
  - Leaf transmission is more critical for IMRT than 3DCRT because MLCs shadow the treatment area for a large portion of delivered MU

- **MLC leaf penumbra**
  - should be measured with high resolution detector (such as film or diode)
  - a beam model based on a chamber with an inner diameter >0.3cm may not produce accurate IMRT plans

AAPM Report 82, 2003
MLC Leakage

- Leakage types:
  - transmission through leaves
  - interleaf leakage
- Often the treatment planning system uses the “average leakage”
  - in this case, leakage should be measured with a detector large enough to provide an average value
MLC Penumbra
Leaf position may be calibrated at:

- actual position
- 50% dose profile
  - Requires minimum leaf distance. Opposing leaves at same position would collide!
  - Calibration can be done in water phantom
- best position for abutting leaves
  - Gives optimal dose distribution with abutting segments
  - Slight difference from 50% dose profile
  - Calibration can be done using strip test

most important: make sure linear accelerator & treatment planning system use same definition for leaf edge!
Dosimetric Leaf Gap (DLG) or Dosimetric Leaf Separation (DLS)

• DLG is a systematic offset introduced in the modeled leaf position
• Introduced into TPS to match the linear accelerator

Figure 4.5 Film measurement of an IMRT field delivered using the sliding window technique of a head-and-neck treatment plan transferred to a phantom. The measured and calculated dose distributions along the red line have been compared. The correct value of the DLS parameter for this set-up was 2.6 mm. With this value the calculated and measured data agreed very well and are all within gamma criteria of 3% local dose difference and 2 mm DTA. The calculations were repeated by using a larger DLS of 3.1 mm. As a result 9% of the area inside the 0.14 Gy isodose area had a gamma value larger than 1.
DLG Measurement

Leaf gap sweeps across open field

Measure output using ion chamber at center of field

Vary the gap size
DLG Measurement

leaf gap = line intercept
Dynamic MLC IMRT:

• Tests include:
  – MLC speed test: deliver stepwise intensities with all leaf pairs moving at different speeds
  OR
  – ion chamber reading for 1cm sliding gap delivered with varied MU
    • MLC speed will vary given a different MU delivered for the same MLC sequence
    • chamber reading should be directly proportional to MU
    • chamber checks central leaves; film / EPID could be used to check multiple leaves

IMRT Commissioning:
General issues for IMRT using physical attenuators

• Treatment planning system:
  – beam hardening
  – scatter from attenuator

• Delivery system:
  – Choice of attenuation material
  – Machining accuracy
  – Placement accuracy

Relevant References:


in many cases IMRT requires a stricter tolerance than 3D
2. Treatment Planning System Commissioning
IMRT Commissioning: Treatment Planning System

- Difficult to determine if differences between measurement & calculation are due to the planning system, delivery system, or measurement technique
  - Delivery system should be commissioned separate from the treatment planning system
Treatment Planning System Commissioning
Aspects Requiring Special Attention for IMRT

- IMRT is an extension of 3D Treatment Planning
  - same commissioning requirements as for 3D planning + some IMRT specific tasks
- IMRT specific aspects:
  - inverse optimization
    - the optimization process requires more stringent accuracy of volume determinations, beam modelling and DVHs, including the effect of dose grid on these parameters
    - Guidelines & reports describe verification tests for DVH calculation, etc.
    - These details can be verified collectively by a “users group” for a specific planning software
  - leaf sequencer
    - Leaf sequencing algorithm is commissioned together with the planning process (rather than separately)
    - need to perform some verification if & when a new leaf sequence algorithm is introduced
  - dose calculation
TPS Verification:  
Dose Calculation Considerations

• definition of leaf positions in TPS
• beam profiles of small segments & abutting fields (step & shoot)
• beam profiles of small fields (sliding window)
• tongue & groove effect
• leaf transmission
• small field output factors & depth dose curves
• dose distributions in inhomogeneous phantoms irradiated with small fields
• dose distributions for typical site specific fields
• dose distributions for representative test patients
TPS Verification Procedure

- Start simple & then advance to more complex tests.
- Example:
  - single beam on flat phantom with controlled intensity pattern
  - multiple beams on flat phantom with controlled intensity pattern
  - multiple beams treating hypothetical targets in flat phantom
  - multiple beams treating hypothetical targets in anthropomorphic phantom

goals:
- verify accuracy of beam parameters in simple, easily analyzed situations
- determine level of accuracy to be expected in clinical situations
Fig. III.4. The dose profile measured with film across one line of a random intensity pattern (plan = dotted, film = solid), showing some systematic differences in low intensity regions.
IMRT “Test Suite”

AAPM Task Group 119 Report on IMRT Commissioning includes:

- a “test suite” of treatment planning geometries to verify the treatment planning & delivery system
  - structures on square (solid water) phantom
  - optimization constraints
- agreement rates from multiple institutions as a baseline
  - point dose measurements (ion chamber)
  - planar dose measurements (film)
IMRT “Test Suite”

- AAPM TG119 Test Suite:
  - AP-PA
  - Bands
  - Multi-target
  - Prostate
  - Head & Neck
  - C-shape (easy)
  - C-shape (hard)

different optimization criteria / constraints
IMRT “Test Suite”

Multi-Target

Fig. 2. Multitarget structures: Central target, superior target, and inferior target. These three cylindrical targets are stacked along the axis of rotation. Each has a diameter of approximately 4 cm and length of 4 cm. Coronal and transverse views are shown.

C-Shape

Fig. 5. CShape structures: CShape PTV and core. The center core is a cylinder 1 cm in radius. The gap between the core and the PTV is 0.5 cm, so the inner arc of the PTV is 1.5 cm in radius. The outer arc of the PTV is 3.7 cm in radius. The PTV is 8 cm long and the core is 10 cm long. Transverse and 3D views are shown.
IMRT “Test Suite”

Fig. 3. Mock prostate structures: The prostate CTV, PTV, rectum, and bladder. The prostate CTV is roughly ellipsoidal with RL, AP, and SI dimensions of 4.0, 2.6, and 6.5 cm, respectively. The prostate PTV is expanded 0.6 cm around the CTV. The rectum is a cylinder with diameter of 1.5 cm that abuts the indented posterior aspect of the prostate. The PTV includes about 1/3 of the rectal volume on the widest PTV slice. The bladder is roughly ellipsoidal with RL, AP, and SI dimensions of 5.0, 4.0, and 5.0 cm, respectively, and is centered on the superior aspect of the prostate. Transverse and coronal views are shown.

Fig. 4. Mock head/neck structures: HN PTV, cord, and parotid glands. The PTV is retracted from the skin by 0.6 cm. There is a gap of about 1.5 cm between the cord and the PTV. The parotid glands are to be avoided and are at the superior aspect of the PTV. Transverse and 3D views are shown.
TG119 Multi-Institutional Baseline

<table>
<thead>
<tr>
<th>Institution</th>
<th>Accelerator</th>
<th>Delivery technique</th>
<th>Planning system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mayo Clinic Arizona</td>
<td>Varian 21EX</td>
<td>DMLC</td>
<td>ECLIPSE V7.5</td>
</tr>
<tr>
<td>Thomas Jefferson University Hospital</td>
<td>Elekta Synergy S</td>
<td>SMLC</td>
<td>CMS XIO V3.1</td>
</tr>
<tr>
<td>Robert Wood Johnson University Hospital</td>
<td>Varian 21EX</td>
<td>DMLC</td>
<td>ECLIPSE V7.5</td>
</tr>
<tr>
<td>Memorial Sloan Kettering Cancer Center</td>
<td>Varian Trilogy</td>
<td>DMLC</td>
<td>In-house</td>
</tr>
<tr>
<td>Karmanos Cancer Center/Wayne State University</td>
<td>Varian 23EX</td>
<td>DMLC</td>
<td>ECLIPSE V7.5</td>
</tr>
<tr>
<td>Karmanos Cancer Center/Wayne State University</td>
<td>Tomotherapy Hi-Art</td>
<td>BinaryMLC</td>
<td>TOMOTHERAPY V3.0</td>
</tr>
<tr>
<td>University of California at San Francisco</td>
<td>Siemens Oncor C</td>
<td>SMLC</td>
<td>PINNACLE V8.0d</td>
</tr>
<tr>
<td>University of Florida</td>
<td>Elekta Synergy</td>
<td>SMLC</td>
<td>PINNACLE V8.0d</td>
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<td>Virginia Commonwealth University</td>
<td>Varian Trilogy</td>
<td>DMLC</td>
<td>PINNACLE V8.0d</td>
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<tr>
<td>Charleston Radiation Therapy Consultants</td>
<td>Siemens Primus</td>
<td>SMLC</td>
<td>PINNACLE V7.4f</td>
</tr>
</tbody>
</table>

variety of linear accelerators, delivery techniques, & planning systems
**TG 119 Multi-Institutional Baseline: Point Dose**

**TABLE VII.** High dose point in the PTV measured with ion chamber: \([(\text{measured dose}) - (\text{plan dose})]/\text{prescription dose}, \text{averaged over the institutions, with associated confidence limits.}\]

<table>
<thead>
<tr>
<th>Test</th>
<th>Location</th>
<th>Mean</th>
<th>Standard deviation ((\sigma))</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multitarget</td>
<td>Isocenter</td>
<td>0.001</td>
<td>0.017</td>
<td>0.030</td>
<td>−0.020</td>
</tr>
<tr>
<td>Prostate</td>
<td>Isocenter</td>
<td>−0.001</td>
<td>0.016</td>
<td>0.022</td>
<td>−0.026</td>
</tr>
<tr>
<td>Head and neck</td>
<td>Isocenter</td>
<td>−0.010</td>
<td>0.013</td>
<td>0.011</td>
<td>−0.036</td>
</tr>
<tr>
<td>CShape (easier)</td>
<td>2.5 cm anterior to isocenter</td>
<td>−0.001</td>
<td>0.028</td>
<td>0.038</td>
<td>−0.059</td>
</tr>
<tr>
<td>CShape (harder)</td>
<td>2.5 cm anterior to isocenter</td>
<td>−0.001</td>
<td>0.036</td>
<td>0.054</td>
<td>−0.061</td>
</tr>
<tr>
<td>Overall combined</td>
<td></td>
<td>−0.002</td>
<td>0.022</td>
<td>0.025</td>
<td>−0.001</td>
</tr>
<tr>
<td>Confidence limit</td>
<td>= (</td>
<td>\text{mean}</td>
<td>+ 1.96(\sigma))</td>
<td>0.045</td>
<td></td>
</tr>
</tbody>
</table>

\(\sigma = \sim 2\%-3.6\%\)

**TABLE IX.** Low dose point in the avoidance structure measured with ion chamber: \([(\text{measured dose}) - (\text{plan dose})]/\text{prescription dose}, \text{averaged over the institutions, with associated confidence limits.}\]

<table>
<thead>
<tr>
<th>Test</th>
<th>Location</th>
<th>Mean</th>
<th>Standard deviation ((\sigma))</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multitarget</td>
<td>4 cm inferior to isocenter</td>
<td>−0.008</td>
<td>0.019</td>
<td>0.014</td>
<td>−0.050</td>
</tr>
<tr>
<td>Prostate</td>
<td>2.5 cm posterior to isocenter</td>
<td>0.000</td>
<td>0.018</td>
<td>0.030</td>
<td>−0.025</td>
</tr>
<tr>
<td>Head and neck</td>
<td>4 cm posterior to isocenter</td>
<td>0.004</td>
<td>0.024</td>
<td>0.061</td>
<td>−0.017</td>
</tr>
<tr>
<td>CShape (easier)</td>
<td>Isocenter</td>
<td>0.010</td>
<td>0.024</td>
<td>0.050</td>
<td>−0.037</td>
</tr>
<tr>
<td>CShape (harder)</td>
<td>Isocenter</td>
<td>0.009</td>
<td>0.025</td>
<td>0.055</td>
<td>−0.021</td>
</tr>
<tr>
<td>Overall combined</td>
<td></td>
<td>0.003</td>
<td>0.022</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confidence limit</td>
<td>= (</td>
<td>\text{mean}</td>
<td>+ 1.96(\sigma))</td>
<td>0.047</td>
<td></td>
</tr>
</tbody>
</table>

\(\sigma = \sim 2\%\) of prescription

largest uncertainty for most complicated plans
# TG 119 Multi-Institutional Baseline: Film

## TABLE XI. Composite film: Percentage of points passing gamma criteria of 3%/3 mm, averaged over the institutions, with associated confidence limits.

<table>
<thead>
<tr>
<th>Test</th>
<th>Location</th>
<th>Mean</th>
<th>Standard deviation ($\sigma$)</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Number of submissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multitarget</td>
<td>Isocenter</td>
<td>99.1</td>
<td>0.9</td>
<td>100</td>
<td>97.5</td>
<td>8</td>
</tr>
<tr>
<td>Prostate</td>
<td>Isocenter</td>
<td>98.0</td>
<td>2.24</td>
<td>99.8</td>
<td>94.2</td>
<td>7</td>
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<tr>
<td></td>
<td>2.5 cm posterior</td>
<td>93.2</td>
<td>7.6</td>
<td>99.9</td>
<td>85</td>
<td>3</td>
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<tr>
<td>Head and neck</td>
<td>Isocenter</td>
<td>96.2</td>
<td>3.0</td>
<td>100</td>
<td>92.4</td>
<td>8</td>
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<td></td>
<td>4 cm posterior</td>
<td>97.6</td>
<td>1.5</td>
<td>98.9</td>
<td>95.6</td>
<td>4</td>
</tr>
<tr>
<td>CShape (easier)</td>
<td>Isocenter</td>
<td>97.6</td>
<td>3.9</td>
<td>100</td>
<td>88.9</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>2.5 cm anterior to isocenter</td>
<td>93.9</td>
<td>5.0</td>
<td>99.6</td>
<td>87.9</td>
<td>5</td>
</tr>
<tr>
<td>CShape (harder)</td>
<td>Isocenter</td>
<td>94.4</td>
<td>6.0</td>
<td>99.4</td>
<td>86.2</td>
<td>5</td>
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<tr>
<td></td>
<td>2.5 cm anterior to isocenter</td>
<td>93.0</td>
<td>7.2</td>
<td>99.9</td>
<td>81.3</td>
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<tr>
<td>Overall combined</td>
<td></td>
<td>96.3</td>
<td>4.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Confidence limit = (100 – mean) + 1.96$\sigma$

12.4 (i.e., 87.6% passing)

## TABLE XIII. Per-field measurements: Average percentage of points passing the gamma criteria of 3%/3 mm, averaged over the institutions, with associated confidence limits.

<table>
<thead>
<tr>
<th>Test</th>
<th>Mean</th>
<th>Standard deviation ($\sigma$)</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
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<tr>
<td>Multitarget</td>
<td>97.8</td>
<td>3.5</td>
<td>99.8</td>
<td>90.8</td>
</tr>
<tr>
<td>Prostate</td>
<td>98.6</td>
<td>2.4</td>
<td>100</td>
<td>93.3</td>
</tr>
<tr>
<td>Head and neck</td>
<td>98.1</td>
<td>2.0</td>
<td>100</td>
<td>94.2</td>
</tr>
<tr>
<td>CShape (easier)</td>
<td>97.4</td>
<td>2.8</td>
<td>99.8</td>
<td>93.0</td>
</tr>
<tr>
<td>CShape (harder)</td>
<td>97.5</td>
<td>2.6</td>
<td>99.9</td>
<td>94.0</td>
</tr>
<tr>
<td>Overall combined</td>
<td>97.9</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Confidence limit = (100 – mean) + 1.96$\sigma$

7.0 (i.e., 93.0% passing)

35
3. Dosimetric verification per plan / site
Dosimetric verification per planning site

What to do when a new IMRT treatment technique is to be introduced (if it is relatively unique from current practice):

• prepare a sample of representative treatment plans
  – solidify details for treatment planning, delivery, & QA processes
• make a thorough set of verification measurements for the sample plans
• *goal is be confident of the robustness & dosimetric accuracy for the new technique*
Suggested Layers of Quality Assurance:

- **Level 1**: Machine QA: dosimetric and geometric characteristics within predefined tolerances
- **Level 2**: QA of planning system and data consistency with machine
- **Level 3**: 1D-2D dosimetry of treatment components (IM beams, segments, ...)
- **Level 4**: 3D dosimetry of entire treatment delivery

Introducing a new technique: work from top down. If discrepancies exist, move down the list until the problem is resolved. Stop here if agreement is good.
4. Independent QA / Credentialing
Independent QA / Credentialing

- Imaging and Radiation Oncology Core (IROC) (formerly RPC) offers independent QA services
  - absolute dose output check
  - IMRT phantoms (point dose & film measurement) used to credential for clinical trials
- Alternative: cross check absolute dose measurement with another (nearby) radiation oncology center

Head and Neck Phantom

The head and neck phantom consists of the following:
- Primary PTV containing 4 TLD
- Secondary PTV containing 2 TLD
- Organ at risk containing 2 TLD
- GafChromatic® film in axial and sagittal planes
References:

• ESTRO Guidebook 9: GUIDELINES FOR THE VERIFICATION OF IMRT (2008)

• AAPM:
  – TG119: IMRT commissioning: Multiple institution planning and dosimetry comparisons (2009)
  – TG120: Dosimetry tools and techniques for IMRT (2011)