Dosimetry Metrology for IMRT

Jean M. Moran, Ph.D.

AAPM Summer School
June 2003

The Department of Radiation Oncology
University of Michigan

Outline

• Acceptance testing
• Detectors for commissioning
• Phantoms
• Dosimetry analysis tools
• Commissioning tests
  – Varying complexity and geometry
• Potential Pitfalls
• Summary

Acceptance

• Prior to purchase and installation, review manufacturer’s acceptance tests
• If needed, adapt tests and tolerances with manufacturer in purchase order
• Test basic functionality of equipment
• Tests may be dependent on the MLC design

Physical MLC Characteristics

<table>
<thead>
<tr>
<th>Feature</th>
<th>Elekta</th>
<th>Siemens</th>
<th>Varian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Width</td>
<td>40x40 cm²</td>
<td>40x40 cm²</td>
<td>40x40 cm²</td>
</tr>
<tr>
<td>(40x27 cm²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaf ends</td>
<td>Rounded</td>
<td>Divergent</td>
<td>Rounded</td>
</tr>
<tr>
<td>Leaf width</td>
<td>1 cm</td>
<td>1 and 6.5 cm</td>
<td>0.5 and 1 cm</td>
</tr>
<tr>
<td>Length</td>
<td>32.5 cm</td>
<td>31 cm</td>
<td>16 cm (14.5 cm Carriage)</td>
</tr>
<tr>
<td>Interdigitation</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Gap size</td>
<td>at cm gap</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Effect of Rounded Leaf Ends & Linear Motion

- Linear leaf motion
- Uncorrected
- Corrected
- Cold
- Hot
- Uniform Correction
- Leaf position offset = Xrad-Xlight

Graves 2001
Static MLC Testing

- Carriage skew
  - Orientation of MLC carriages in the accelerator head
  - Determined by measurement with feeler gauges for very small field size
  - Important to prevent collisions especially for systems with interdigitation of leaves
  - Verify with film
- Alignment of each leaf bank to central axis
- Leaf position reproducibility and accuracy
  - Verify with graph paper

MLC Transmission

- Dependent on system design
- Values range from 1.5 to 3% for midleaf and interleaf transmission

Tongue and Groove Effect

Caused by overlap of leaves and leaf design

Uniform Square Field Illustration of TG Effect

Area in Red Never Directly Exposed

Cold Spots from T&G Effect

~25% cold spot where leaves overlap

DMLC and/or SMLC Mode Tests

- Leaf speed
- Dose rate evaluation
- Leaf position tolerance and reproducibility
- Leaf acceleration and deceleration
- Rounded leaf tip transmission
- Beam stability (output, flatness, symmetry, linearity)
- Interrupted treatments
Example Test: FenceTest

- All leaves move across field and deliver dose to small field gap (0.1 or 0.2 cm)
- Sensitive to errors of 1 mm in leaf position

Equipment and Software for IMRT Commissioning

- Ideal measurement system:
  - Excellent spatial resolution, accuracy, tissue equivalent response, provide 3-D data, portable to multiple phantoms, and easy to use
- Multiple detectors required:
  - Verifying IMRT fields is more complex than static fields
  - Profiles along major axes in a water phantom are insufficient for characterizing systems
  - Profiles are also time-consuming to obtain in water phantom for IMRT delivery

Equipment

- Depth dose and profiles in water
  - Ion chamber – required for absolute dose measurements
  - Ion chamber or linear diode array
  - Note: Depth dose curve measurements must be made with a repeat delivery for each datapoint on the curve (delivery stability)
- Detector arrays are useful for profile measurements in water but 2-D detectors are still required
- 2-D measurement methods
  - Film
  - Detector arrays

Detector Characterization

- Linearity
- Energy dependence
- Stem and cable effects
- Angular response
- Calibrated if for absolute measurements
- Small field detectors required for small field characterization
  - Sensitive to position
  - Detector should be smaller than homogeneous region of dose to be measured

1-D Detector Characteristics

<table>
<thead>
<tr>
<th>Detector</th>
<th>Measurement Volume (cm³)</th>
<th>Sensitive Area (cm²)</th>
<th>Diameter (cm)</th>
<th>Thickness (cm)</th>
<th>Effective Point of Measurement (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro-chamber</td>
<td>0.003</td>
<td>0.24</td>
<td>0.6</td>
<td>NA</td>
<td>0.2</td>
</tr>
<tr>
<td>p-type Si diode</td>
<td>0.3</td>
<td>0.6</td>
<td>0.4</td>
<td>0.06</td>
<td>0.6</td>
</tr>
<tr>
<td>Stereotactic diode</td>
<td>NA</td>
<td>0.011</td>
<td>0.45</td>
<td>0.006</td>
<td>0.27</td>
</tr>
<tr>
<td>Pinpoint chamber</td>
<td>0.013</td>
<td>0.010</td>
<td>0.2</td>
<td>NA</td>
<td>0.06</td>
</tr>
<tr>
<td>MOSFET</td>
<td>NA</td>
<td>0.064</td>
<td>NA</td>
<td>0.1</td>
<td>NA</td>
</tr>
<tr>
<td>Diamond</td>
<td>0.0019</td>
<td>0.0004-0.037</td>
<td>0.27</td>
<td>0.025</td>
<td>0.1</td>
</tr>
</tbody>
</table>

1-D Detectors

<table>
<thead>
<tr>
<th>DETECTOR</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro-chamber</td>
<td>Poorer resolution than diodes</td>
</tr>
<tr>
<td>p-type Si diode</td>
<td>Over-respond to low energy photons Martens et al. 2000</td>
</tr>
<tr>
<td>Stereotactic diode</td>
<td></td>
</tr>
<tr>
<td>Pinpoint chamber</td>
<td></td>
</tr>
<tr>
<td>MOSFET</td>
<td>Non-linear dose response for &lt;30 cGy Chuang et al 2002</td>
</tr>
<tr>
<td>Diamond</td>
<td></td>
</tr>
</tbody>
</table>
MOSFET System

- Excellent spatial resolution
- Automatic and immediate readout
- Can be re-used immediately
- Linear dose response
- Response independent of depth

C. Chuang, UCSF

MOSFET Consistency

Cynthia Chuang, UCSF

TLDs

- TLDs must be characterized
  - Time consuming
- Reusable
- Achievable accuracy: 2-3%
- Automatic reader required for multiple TLD measurements

TLD Holder for Phantom Measurements


2-D Detectors

- Film
  - Radiographic: XV and EDR
  - Radiochromic
- Beam imaging system, CCD, SLIC, AMFPI
  - EPID systems attached to gantry
  - Investigated more for pre-treatment QA currently

Radiographic Film

- Advantages
  - Excellent spatial resolution
  - Readily available
  - Less expensive than other 2-D systems
- Disadvantages
  - Over-response to low energies
  - Dependent on QA of film batch
  - Dependent on processor and digitizer QA
  - Sensitive to storage conditions
  - Need to measure the response to dose for each experiment
Radiochromic Film: Advantages

- Decreased sensitivity to low energy photons compared to radiographic film
- No processing
  - Film changes color with irradiation
- Insensitivity to visible light
- High spatial resolution


Radiochromic Film: Disadvantages

- Non-uniform film response
  - Can be minimized by using double-exposure technique
- Response dependent on time and temperature
- More expensive than radiographic film
- Digitizer response is dependent on the light source of the digitizer and may need to be modified


Active Matrix Flat Panel Dosimeter (AMFPD)

512 x 512 pixels
0.508 mm pitch
26.0 x 26.0 cm


Example: SMLC Delivery

Non-commercial system
AMFPD at 10 cm depth in solid water
184 µm
600 µm/min
d<16 cm

Gel Dosimetry: Advantages

- Obtain 3-D information in one irradiation
- Gels can be prepared with different density therefore ideal for heterogeneous measurements
- Gel can be used in containers of different shapes
- Ideal for anthropomorphic phantoms

Gel Dosimetry: Disadvantages

- Sensitive to many factors such as time, preparation, temperature
- Optical reader requires cylindrical container for gel
- MR time is often limited and expensive (unless dedicated scanner)
  - Long scan times are required to increase accuracy of readout
  - E.g. 5% accuracy over 10 hr scan time (Gum et al. 2002)
- Interface of gel and container results in less accurate readout at edges of the gel
- Not ready for routine use in the community

Considerations for Phantoms

- Fiducials for reproducible setup of phantom and detectors
- Flexibility to accommodate different detectors
- Simple vs. anthropomorphic
- Homogeneous or heterogeneous

Water Tank

- Restricted to gantry at 0 degrees
  - Unless mylar window for 90 degrees
- Flexibility in chamber position
- Important for basic depth dose and profile measurements
- Output, flatness, symmetry, and linearity assessment

**Water-equivalent Plastics**

- Flat phantoms with custom chamber inserts
  - Accommodate film at multiple depths
  - Detector position only varies with depth
- Cylindrical phantoms (plastic or water filled)
  - Ion chamber at single position
  - Possibly hold films
- Can be customized to hold various detectors and have multiple positions

---

**Simple Geometric Phantom**


---

**IMRT Verification Phantom**


---

**Cylindrical Phantom: Ion Chamber and MOSFETs**

- C. Chuang, UCSF

---

**Spiral Phantom for Dosimetric Verification**


---

**RPC Head Phantom**

- TLDs in Target Volumes
  - Radiochromic film through multiple plans
  - Delivery is required by RTOG for participation in IMRT trials
Anthropomorphic Phantom for Gel Dosimetry


Dosimetry Analysis Software

- Transfer patient fluence maps and beam geometry to phantom geometry
- 2-D dose difference displays with colorwash
- DVHs
- Highlight of differences
- Gamma analysis
  - % agreement and distance-to-agreement

Phantom Measurements

- Calculate IMRT plan for each field in measurement geometry
- Film measurement at depth for individual field at gantry=0

Dosimetric Analysis: Overlay of Isodose Lines

Dosimetric Analysis: Dose Color Wash

Dosimetric Analysis: Dose Difference Display
Dosimetric Analysis:
Dose Difference and DTA

Reference Evaluated

3% Dose Difference
3 mm DTA

D. A. Low – Washington University

Dosimetric Analysis: Gamma Evaluation

3%/3 mm 5%/5 mm

D. A. Low – Washington University

Simple Geometry Tests

- Leaf position reproducibility in dynamic or step-and-shoot mode
- Effect of gravity on leaf position accuracy and reproducibility
- Sweeping gap test
- Fence test

Simple Geometry Tests

- Leaf speed stability
- Leaf acceleration/deceleration
- Output checks for small to large fields – Including smallest field size – 1 x 1 cm²
- MLC limits (field size restrictions)
- Depth dose curve measurements

Geometric Tests

Acceptance tests and quality control (QC) procedures for the clinical implementation of intensity modulated radiotherapy (IMRT) using inverse planning and the sliding window technique experience from five radiotherapy departments: Van Esch et al Radiotherapy Oncology 65: 53-70 (2002).

Complex Cases – Simple Geometry

Evaluate dose across field as a function of regional beamlet intensity.

Complex Geometry: Anthropomorphic phantom


Potential Pitfalls

- Limit number of monitor units per segment to verified Linac behavior
- Limit field width for IMRT
- Overshoot-undershoot phenomenon
- Incorrect tolerance value
- Integration with record-and-verify system

Potential Pitfalls: Prior to Measurements

- Verify all equipment is functioning properly
  - Film processor, digitizer
  - Detectors, cables, electrometers (automatic leakage correction)
  - TLD reader, ovens
- Input/output to treatment planning system
- Standardize measurement setup when possible
- Monitor software and hardware changes and QA

Detector Issues

Dose (cGy)

Volume
Detector Position

- Small ion chambers are very sensitive to position
- Position should be considered with respect to MLC design
  - Example: CAX of Varian MLC is a junction of four 0.5 cm wide leaves

Ratio Calc/Ion Chamber - CAX

Effect of Leaf Position Offset on IMRT

- No leaf offset correction: 0-12% errors
- With leaf offset corrected: +/- 5%

Overshoot Phenomenon: Example Varian System SMLC Delivery


System Communication Delay

- 0.055 second

MLC Dynamic Log File (Dynalog)

- Varian 21 EX
- Expected and actual leaf positions
- Beam hold-off events
- Position tolerance setting
- Recorded approximately every 55 ms
- Information can be compared to imported 2-D information

Deviation in Leaf Trajectory

Expected Trajectory
Actual Trajectory
MLC Beam Hold-Off

DMLC: Effect of Incorporating Machine Limitations

BEFORE
44 μm, tolerance 0.1 mm
no gap: 137 beam hold-offs

AFTER
54 μm, tolerance 0.25 mm
gap 1.1 mm: No beam hold-offs

Summary

- Basic MLC characteristics should be tested in static mode prior to IMRT testing
- IMRT tests should be specific to delivery mode and device
- Be aware of potential issues with delivery systems that may need further investigation
- Multiple detectors and phantoms are typically required for IMRT commissioning
- Quantitative dose analysis tools are required for proper evaluation of delivery

Summary

- Measurements may show dosimetric – mechanical differences that planning systems may not model at this time
- Need to know the limits of the mechanical systems and combination of software + delivery
- Continued need to improve software for delivery system, measurement devices, phantoms, and dose analysis tools
Acknowledgements

University of Michigan
Dale Litzenberg
Jeff Radawski
Tim Nurushev
Benedick Fraass

Dan Low – Washington University
Cynthia Chuang - UCSF