The Use of 2D Detector Arrays and Cylindrical Phantoms for IMRT QA

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DISCLOSURE

➢ I have no conflicts of interest to disclose.
Learning Objectives

The attendee will gain an understanding of:

- the rationale for patient-specific QA for IMRT delivery
- routine IMRT QA methods using “arrays” and their limitations
- issues related to determining delivery “acceptability”
Why should we perform patient-specific IMRT QA?
It is STILL necessary to validate each individual IMRT treatment plan with dosimetric measurements before delivery

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For

“…even if our current tests are insensitive to small but significant errors, basic failures that can be devastating or even of lesser consequence, can be found at this stage, before the patient is placed on the treatment couch.”

“…per patient QA is necessary for the foreseeable future if only as a means to catch gross error.”

Against

“Choosing a single patient-specific measurement performed before the course…of treatment …may also create a false sense of safety with other, more severe failure modes being overlooked.”

“If our validation measurements are based on the delivery files, how, if at all, do we ensure that these files do not get corrupted sometime between the measurement and the end of treatment…”
MU = TD / (Norm x TMR x Sc x Sp x TF x WF x IVS....)
Even with calculation programs we typically get dose to a point; not spatial information. We get no information with respect to delivery.
We need to distinguish between IMRT “commissioning” and QA

- Patient-specific “phantom” IMRT QA evaluates delivery only
- Calculational accuracy is determined during commissioning
Routine QA

Prostate (Measured vs Calculated)

Number of Patients

Frequency Bins (% difference)

0.125 cc ion chamber
Calculated vs. Measured IMRT Dose Differences

Agreement Rates
±1% → 36.9% of cases
±2% → 65.3% of cases
±3% → 86.8% of cases
±4% → 96.7% of cases
High Dose Low Gradient Dose Verification

Repeat Measurements

Multiple Point/Plane Dose Verifications (high and low dose regions)

Monte Carlo Verification using .RTP file and patient (and phantom) geometry

MLC Calibration

MU Scaling (use caution; what was the problem?)

Re-planning
Measured distribution
Calculated distribution
Fusion or overlay

97.96% of pixels pass
What is Gamma Analysis or the Gamma Method?

- Comparing the difference between 2 dose distributions may not be sufficient
  - This difference may be large in regions of high dose gradient (even if the isodoses are relatively close to each other)
  - The distance between the isodoses of the 2 distributions may be large in flat dose regions (even if the dose difference is small)

- The Gamma method combines both methods and allows for user-defined pass/fail criteria based on dose difference and isodose distance
  - If both dose and isodose distance are outside the criteria, agreement “fails”
  - If only one parameter is outside the criteria but the other is within, the comparison can still “pass”

Most common IMRT QA delivery approaches

Composite of all beams delivered “straight down”

Composite of all beams delivered through “plan-specific” geometry
No warm and fuzzy feelings

Warm and fuzzy feelings
RapidArc Prostate Case (Coronal View)

What’s this? Approximately 25% (20Gy) right in the Wazoo!
MLCs abutt "inside" jaws. Attempts to correct within TPS were unsuccessful. Correction made in R&V system, and QA repeated successfully.

Collimator rotated to 45° to minimize tongue and groove effect throughout axial arc rotation.
It seems intuitive that MLC leaf position inaccuracy is unlikely to occur with gravity normal to the direction of leaf travel and is more likely to occur at “other” gantry angles.
Note: we also perform a “Dry Run” with the patient on the treatment table for all non-coplanar beam arrangements prior to 1st treatment delivery
So what are we checking?

- Electronic Transfer (Planning system to R&V to Linac)
- Delivery Accuracy (demanding physicians and innovative planners “stress” the planning systems)
- Most Probable Causes for Failure (MLC, unknown attenuation, etc.)
- Potential Collisions
• Air-vented pixel ionization chambers with lowest angular dependence
• Parallel read-out of all ionization chambers without deadtime. Down to 20 msec/sample
• Highest spatial resolution: 1020 ionization chambers in an active area of 24 x 24 cm²
• Multiple configurations in 5 cm increments (MULTICube: plastic water)

Removable film cassette with registration points for independent film verification at same measurement plane as the MatriXX Evolution

Courtesy iba Dosimetry
MatriXX

- >1000 IMRT cases QA’d with this device at FCCC
- Easy to use software
- Successfully used for rotational therapy (VMAT)
- Single plane array (7.62mm center-to-center)
- Volume averaging effect (ion chambers)
- Angular dependence
- Ionchamber substrate
- Linac output correction method (needs help)
- Heavy phantom
CT scan of array and phantom

Isocentric plane (external fiducials)

Effective plane of measurement (AP only)

Effective plane of measurement (center of chambers)

Courtesy Iavor Veltchev, Ph.D.
Angular dose dependency of MatriXX TM and its calibration

Luciant D. Wolfsberger, Matthew Wagar, Paige Nitsch, Mandar S. Bhagwat, and Piotr Zyganski

Division of Medical Physics and Biophysics, Department of Radiation Oncology, Dana-Farber Cancer Institute/Brigham and Women's Hospital, Harvard Medical School, Boston MA, USA

...the rather large dose discrepancy between AP and PA fields measured with MatriXX Evolution cannot be accounted for by water equivalent path length corrections...is most likely due to effects occurring at the air-high-Z material interfaces.

\[
CF(\theta) = \frac{D(\theta)}{D_{ref}(\theta)} \quad D_{QA}^{calib}(\theta) = \frac{D_{QA}(\theta)}{CF(\theta)}
\]

...decreased overall uncertainty in the cumulative plan measurement from about 3% to the level of about 1%.

Fig. 3. Angular dependency of one of the MatriXX detectors. Data points are the measured doses relative to A12. Solid line is a cubic interpolation of mirrored data $CF(\theta) \rightarrow (CF(\theta) + CF(360^\circ - \theta))/2$. 
Evaluation of MatriXX for IMRT and VMAT dose verifications in peripheral dose regions

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Boston, Massachusetts 02115

Med. Phys. 37 (7), July 2010

Angular dependence

Dose bias ($\delta$) (offset in $D_{\text{Max}}$) independent of dose level and can be determined in absence of irradiation

Linearity

Over-response to scattered dose ($\beta$)

Corrections made outside of OMNIPRO-I’MRT software in MATLAB (The MathWorks, Inc., Natick, MA)
CYLINDRICAL PHANTOM
Arc Therapy

Courtesy Sun Nuclear Corp.
The ArcCheck consists of 1386 N type diodes in a cylindrical phantom.

- Diodes are embedded in a spiral pattern with 10 mm spacing in a 2.85 cm outer and 2.90 cm inner acrylic (1.17 g/cm3) layer.
- 15cm diameter phantom central hole; can host homogeneous plug with a chamber insert.
- The ArcCheck measures in 50ms intervals and can save data as a function of time.

Sun Nuclear Corp.
Comparison with 2D array

The system measures entrance and exit dose (before and after isocenter) at 2 effective depths for every angle.
Measurement and Calculation Dose Comparison using the MapCheck Software Interface
General observations

Can always measure dose through target region of dose distribution
May need to create “multiple” verification plans with array through different aspects of dose distribution (requiring multiple deliveries)

Will always acquire “more” data than a single plane array
Will probably NOT have array intersecting target to any appreciable degree (measuring in the relatively low to intermediate dose regions)
RapidArc Prostate Case (ArcCHECK)
Calibration

- **Array Calibration**
  - The array calibration is performed by the manufacturer and a calibration file is supplied with the system. This calibration is done to equalize the response for each of the 1386 diodes.

- **Absolute Dose Calibration**.
  - Input a known dose for given MU into the software. This dose corresponds to the top diode location (the diode that has the smallest SDD e.g. 89.6 cm).
Absolute Dose Calibration recipe (for a given photon energy)

- Perform routine linac output check and determine nC/cGy.
- Setup AC phantom with the plug. Deliver 100 MU and determine the central dose.
- Use TMR ratio for effective pathlengths (acrylic to water) and inverse square law to determine dose to calibration diode.
Evaluation

- Does the dose accumulated in the peripheral diodes correspond to the central phantom dose?
- Arc delivery to AC phantom w/plug and 0.125cc ion chamber for central dose measurement (comparisons with TPS and MC)
- Arc delivery to AC system cylindrical array for gamma evaluation.
- Used 10 clinical cases for comparisons
- Studied effects of phantom misalignment
10 RapidArc treatments were investigated.

- 6 prostate cases
- Head and neck
- Pelvis
- Liver
- Breast

TPS and MC calculations

- Created verification plans using MV-CT data from vendor
  - For system in general use
  - For system w/ plug
MVCT data

- Less scattering from high Z materials (diode structure)
- Vendor calibration ramp.
- MVCT data resulted in lower dose values that compared favorably with measurements.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>TPS kV CT [cGy]</th>
<th>TPS MV CT [cGy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prostate 1</td>
<td>218.7</td>
<td>216.2</td>
</tr>
<tr>
<td>HN</td>
<td>111.7</td>
<td>110.2</td>
</tr>
<tr>
<td>Breast</td>
<td>155.4</td>
<td>153.3</td>
</tr>
<tr>
<td>Prostate 2</td>
<td>223</td>
<td>220.8</td>
</tr>
<tr>
<td>Prostate 3</td>
<td>221.6</td>
<td>219.3</td>
</tr>
<tr>
<td>Prostate 4</td>
<td>236.9</td>
<td>234.3</td>
</tr>
<tr>
<td>Liver</td>
<td>575.7</td>
<td>569.6</td>
</tr>
<tr>
<td>Pelvis</td>
<td>519.9</td>
<td>515.6</td>
</tr>
<tr>
<td>Prostate 5</td>
<td>233.6</td>
<td>231</td>
</tr>
<tr>
<td>Prostate 6</td>
<td>223.1</td>
<td>220.6</td>
</tr>
</tbody>
</table>
## Central phantom dose

<table>
<thead>
<tr>
<th>Treatment Type</th>
<th>Measured Dose at isocenter (chamber) [cGy]</th>
<th>TPS Dose at isocenter [cGy]</th>
<th>MC Dose at isocenter [cGy]</th>
<th>TPS to meas. [% diff]</th>
<th>MC to meas. [% diff]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prostate 1</td>
<td>215.7</td>
<td>216.2</td>
<td>215.4</td>
<td>0.2</td>
<td>-0.1</td>
</tr>
<tr>
<td>HN</td>
<td>103.4</td>
<td>110.2</td>
<td>110.1</td>
<td>6.6</td>
<td>7.1</td>
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<tr>
<td>Breast</td>
<td>152.8</td>
<td>153.3</td>
<td>150.8</td>
<td>0.3</td>
<td>-1.3</td>
</tr>
<tr>
<td>Prostate 2</td>
<td>213.8</td>
<td>220.8</td>
<td>215.3</td>
<td>3.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Prostate 3</td>
<td>216.1</td>
<td>219.3</td>
<td>214.4</td>
<td>1.5</td>
<td>-0.8</td>
</tr>
<tr>
<td>Prostate 4</td>
<td>237.9</td>
<td>234.3</td>
<td>234.6</td>
<td>-1.5</td>
<td>-1.4</td>
</tr>
<tr>
<td>Liver</td>
<td>565.1</td>
<td>569.6</td>
<td>554.6</td>
<td>0.8</td>
<td>-1.9</td>
</tr>
<tr>
<td>Pelvis</td>
<td>504.4</td>
<td>515.6</td>
<td>503.6</td>
<td>2.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Prostate 5</td>
<td>235.5</td>
<td>231.0</td>
<td>230.5</td>
<td>-1.9</td>
<td>-2.1</td>
</tr>
<tr>
<td>Prostate 6</td>
<td>222.5</td>
<td>220.6</td>
<td>222.1</td>
<td>-0.9</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

Mean: 1.1 0.0
Passing rate for gamma analysis using peripheral diode array

<table>
<thead>
<tr>
<th>Treatment Type</th>
<th>Meas.-TPS Gamma 3%/3mm</th>
<th>Meas.-TPS Gamma 2%/2mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prostate 1</td>
<td>97.4</td>
<td>82.1</td>
</tr>
<tr>
<td>HN</td>
<td>95.1</td>
<td>84</td>
</tr>
<tr>
<td>Breast</td>
<td>94.3</td>
<td>83.9</td>
</tr>
<tr>
<td>Prostate 2</td>
<td>97.6</td>
<td>82.7</td>
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<tr>
<td>Prostate 3</td>
<td>95.9</td>
<td>73.1</td>
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<tr>
<td>Prostate 4</td>
<td>98.8</td>
<td>79.7</td>
</tr>
<tr>
<td>Liver</td>
<td>97.9</td>
<td>81.6</td>
</tr>
<tr>
<td>Pelvis</td>
<td>92.8</td>
<td>79.7</td>
</tr>
<tr>
<td>Prostate 5</td>
<td>97.9</td>
<td>78.4</td>
</tr>
<tr>
<td>Prostate 6</td>
<td>98.3</td>
<td>79.2</td>
</tr>
</tbody>
</table>

Mean: 96.6 80.4
Setup Misalignment Comparison: ArcCHECK vs. MatriXX

- AP misalignment 1, 2, 3, 5, 10 mm
- RL misalignment 1, 2, 3, 5, 10 mm
- Rotation misalignment 1, 2, 3 degrees.
Gamma Analysis

- Measurement and comparison with varying acceptance criteria:
  - 9 acceptance criteria
  - Varying from 1-3% dose and 1-3mm DTA

<table>
<thead>
<tr>
<th>D%</th>
<th>1mm</th>
<th>2mm</th>
<th>3mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>2%</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
</tr>
</tbody>
</table>
(Breast) Gamma criteria for AP misalignment setup

MatrixX 3% 3mm
ArcCheck 3% 3mm
MatrixX 2% 2mm
ArcCheck 2% 2mm
MatrixX 1% 1mm
ArcCheck 1% 1mm

Similar sensitivity to A/P misalignment
(Breast) Gamma criteria for RL misalignment setup

Appears that MatriXX is significantly more sensitive to R/L misalignment.
(Breast) Gamma criteria for rotation misalignment setup

Appears that ArcCHECK is more sensitive to rotational misalignment
Gamma criteria for AP misalignment setup

矩阵X 1%3mm
ArcCheck 1%3mm
矩阵X 3%1mm
ArcCheck 3% 1mm

看起来ArcCHECK对剂量更敏感，而矩阵X对DTA更敏感。

一个可能的解释是，ArcCHECK主要在较低的剂量区域测量，因此等剂量线可能不那么压缩。此外，因为剂量较低，%diff/cGy较大。
Acceptance Criteria

ΔD_M is the dose difference
Δd_M is the distance to agreement

For a reference point at position \( r_r \), receiving dose \( D_r \) the surface representing these acceptance criteria is an ellipsoid defined as:

\[
1 = \sqrt{\frac{\Delta r^2}{\Delta d_M^2} + \frac{\Delta D^2}{\Delta D_M^2}}
\]

where

\[
\Delta r = |r_r - r_c|
\]

is the distance between the reference and comparison point and

\[
\Delta D = D_c(r_c) - D_r(r_r)
\]

is the dose difference at position \( r_c \) relative to the reference dose \( D_r \) in \( r_r \). For a distribution to match the reference it needs to contain at least one point \((r_c, D_c)\) lying within the ellipsoid of acceptance; one point for which:

\[
\Gamma_r(r_c, D_c) = \sqrt{\frac{\Delta r^2}{\Delta d_M^2} + \frac{\Delta D^2}{\Delta D_M^2}} \leq 1
\]

Accuracy of correspondence is determined by the point with the smallest deviation from the reference. This minimal value is referred to as the quality index \( \gamma(r_r) \) of the reference point. The pass-fail criterion becomes:

\[
\gamma(r_r) \leq 1, \text{ correspondence within specified acceptance criteria,} \\
\gamma(r_r) \geq 1, \text{ correspondence is not within criteria}
\]
Plan-Specific Gamma Analysis Acceptance Criteria for Multi-Chamber Arrays

- AAPM TG-119 suggests the value for points passing gamma criteria of 3%/3mm be set to 88-90% using **film** in a composite (not per beam) manner.
- Many physicists choose to utilize the various detector arrays available for IMRT QA.
- The resolution of these arrays is certainly inferior to film.
- Values in between detectors are generated through simple interpolation.
- Many also misinterpret having the number of points pass a criterion at a rate of ~2σ (95% of the time) as setting the passing rate at 95%. This interpretation may lead to an inordinate amount of time searching for the (sometimes meaningless and/or insignificant) reason(s) for a delivery not meeting this value.
- To this end it is important to understand the relationship between film and the clinically used array.
- Additionally, the use of arbitrary dose thresholds may limit the analysis of deliverability of a plan, specifically when comparing plans of different complexities (eg. breast, prostate, H&N).
In order to establish the relationship between film and the ionchamber array we irradiated a series of 10 prostate cases using the same phantom with both detectors in the same plane.

Plans were generated on the Varian Eclipse or CMS XiO treatment planning systems using 10MV photons using heterogeneity corrections.

Films were calibrated using a stepwedge calibration curve taken during the case irradiations.

Analysis was performed with respect to gamma criteria of 3%/3mm and dose thresholds of 10% and 50%.

<table>
<thead>
<tr>
<th>Film (10% threshold)</th>
<th>Array (10% threshold)</th>
<th>Film (50% threshold)</th>
<th>Array (50% threshold)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%/3mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>99.19%</td>
<td>92.12%</td>
<td>99.52%</td>
<td>96.67%</td>
</tr>
<tr>
<td>Difference (abs)</td>
<td>7.07%</td>
<td>2.85%</td>
<td></td>
</tr>
<tr>
<td>2%/2mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>95.76%</td>
<td>80.78%</td>
<td>97.28%</td>
<td>85.76%</td>
</tr>
<tr>
<td>Difference (abs)</td>
<td>14.98%</td>
<td>11.52%</td>
<td></td>
</tr>
</tbody>
</table>
From the table above we can lower the TG-119 range from **88-90%** for film to a conservative **85-87%** for the chamber array.

This is felt to be conservative as we are using a plan-specific threshold of 50% for evaluation.

The graph below illustrates our gamma acceptance for the 1st 329 prostate patients whose IMRT QA was performed with this device.

The average number of pixels evaluated passing the gamma criteria of 3%/3mm and a minimum dose threshold of 50% was 94.58%.

The percentage of cases meeting these criteria was 97.57%.
Conclusions with respect to delivery acceptability

- Need knowledge of TPS model (Li et al. Uncertainties in IMRT dosimetry. Med Phys. 37 (6), June 2010)
- Setup accuracy
- Detection system limitation(s)
- Size of target?
- Non-coplanar beam arrangements?
- Output variation
- Relationship with PTV/PRVs (gamma criteria)