Leveraging Multi-Dimensional Detector Systems for Quality Assurance Including TG-142

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Disclosures

I have a faculty appointment at the University of Michigan Department of Radiation Oncology and I am employed by the Veterans Health Administration.

I’m part of a consortium investigating how Varian Developer Mode can be used to automate linac QA.
I’m not endorsing any commercial or non-commercial product.
Objective

To describe how detector arrays can be used for machine and planning system quality assurance, including implementation methods, advantages, and potential pitfalls.
This discussion will address primarily planar (2D) array devices. Quasi-3D arrays can also be used but planar arrays are often more suitable to linac QA.

Diode or ion chamber arrays can be used. Diodes are smaller (better resolution), ion chambers may offer other advantages (less energy dependence, for example).
1. Introduction

Examples of 2D array devices

- Sun Nuclear Mapcheck 2
- PTW 1500
- IBA MatriXX
- Ritter 2D Arrays
Potential advantages of arrays over scanning water phantoms include:

1. Faster and easier setup.
2. Less prone to setup errors.
3. Measurements take less time.
4. 2D information in one measurement.
5. Easy comparison to baselines.
6. Can mount the device on the gantry head for response as a function of gantry angle.
2. Validating Arrays

All QA devices require commissioning and validation prior to use.

There is no task group report that specifically describes how to commission array devices.
FIRST: Know your system for consistent results:
1. Proper set up (level/aligned, temperature, background measurements, electronics warm up, pre-irradiation).
2. Uniformity and dose calibration methods.
3. Configurations for acquisition (modes, digital frame intervals, sampling criteria, thresholds, etc) and data analysis (formulas, averaging, interpolation, etc). Save screen captures!
4. Angular response (if applicable).
5. Data save/export formats. Save raw data.
6. Dose rate response, especially if FFF beams.
7. Inherent buildup and backscatter.
8. Spatial sampling and extent limitations. (often avoid direct exposure of electronics).
9. What’s inside – recommend you image your device.
Once you are familiar with your array you can perform a thoughtful commissioning. Perform your own testing and consult published results.
2. Validating Arrays

Commissioning an Array system for linac QA:
1. Reproducibility.
2. Dose linearity.
3. Output factors as a function of field size.
4. Sensitivity to changes in collimation.
5. Validation against open and wedged fields.
6. Validation of modulated fields.
7. Comparison to water phantom results.

2. Validating Arrays

Commissioning an Array system for linac QA:

Additional considerations:
8. Instantaneous dose rate dependence.

*Can compare against a standard ion chamber.*

2. Validating Arrays

From Li: Dose rate dependence can be examined by changing source to detector distance. Here ionization chamber and diode arrays are compared.

Many arrays provide real-time display of profiles. Beam steering can be fast and efficient if the method is properly vetted and a large field size with appropriate buildup are used.

Validation against a scanning water phantom is important if you want to use the device for beam steering.
2. Validating Arrays

The IC Profiler, an ionization chamber array, has been characterized against a scanning water phantom.


2. Validating Arrays

Comparison between water tank profiles and profiles acquired with the IC Profiler (labeled “Panel” in the figure).

2. Validating Arrays

Comparison between water tank profiles and profiles acquired with the IC Profiler

Figure courtesy of Song Gao, Ph.D., MD Anderson Cancer Center, ref Gao S, Balter P, Rose M, and Simon W. SU-E-T-645: Qualification of a 2D ionization chamber array for beam steering and profile measurement. Medical Physics. 2015;42:3484-3485.
2. Validating Arrays

Results
16 MeV electron beams, depth 3.0 cm

Comparison between water tank profiles and profiles acquired with the IC Profiler

Figure courtesy of Song Gao, Ph.D., MD Anderson Cancer Center, ref Gao S, Balter P, Rose M, and Simon W. SU-E-T-645: Qualification of a 2D ionization chamber array for beam steering and profile measurement. Medical Physics. 2015;42:3484-3485.
3. Linac QA with Arrays

Linac QA applications include:
1. TG-142 monthly testing
2. TG-142 annual testing
3. Post repair machine validations
4. Post upgrade validations

Array devices are an excellent tool for routine QA of accelerators via constancy tests.
TG-142 specifically mentions detector arrays in the report...

The expansion of tests is also justifiable due to the fact that since TG-40 and post-IMRT, the selection of available QA tools makes annual testing less burdensome; these tools range from 3D water scanning tanks to large area detector arrays. The proper tools should be chosen by matching the detectors and software to the needs and sensitivity requirements.

### 3. Linac QA with Arrays

#### Potential TG142 Monthly Applications

<table>
<thead>
<tr>
<th>Monthly Procedure</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon Beam Profile Constancy</td>
<td>1%</td>
</tr>
<tr>
<td>Electron Beam Profile Constancy</td>
<td>1%</td>
</tr>
<tr>
<td>Dynamic Wedge Factor Check Each Energy</td>
<td>+/- 2%</td>
</tr>
<tr>
<td>Typical Dose Rate Output Constancy</td>
<td>2%</td>
</tr>
<tr>
<td>X-ray and Electron Output Constancy</td>
<td>2%</td>
</tr>
<tr>
<td>Light/Radiation Field Coincidence ?</td>
<td>1mm or 1% (asymmetric jaws)</td>
</tr>
<tr>
<td>Electron Beam Energy Constancy ?</td>
<td>2%/2mm</td>
</tr>
</tbody>
</table>

The tool of choice for checking soft wedges.

II.E.2.c. Detector arrays. A detector array system can be used for simultaneous data acquisition over the entire open beam and offers the most suitable method for soft wedge (dynamic wedge or virtual wedge) profile measurements. The array system may be an ion chamber array (air or liquid-filled) or a diode array, depending on the manufacturer. Since an array of detectors can be placed in various directions up to 180°, the data collection time is reduced significantly.

3. Linac QA with Arrays

Measuring a dynamic wedge with an array.

Fast and efficient!

Planar dose difference map set to show 2% dev in red

Radial profile
Measured in red
Baseline in green

Measured dose dbn
Baseline dose dbn

2/15/2016
Ritter 2D Arrays
There are multiple applications of arrays to TG-142 annual testing.

We will review some of these later in the presentation.
3. Linac QA with

What about redundancy in TG-142?

TG-142 includes overlap on the frequency of certain tests

*Example – profile constancy is tested monthly, while profile flatness/symmetry are tested annually.*

Per TG-142:

> “This overlap in frequency should have some level of independence such that the monthly check would not simply be a daily check.”

Monthly tests performed with one device (e.g. EPID) could be performed annually using a different device (e.g. 2D ion chamber array).
## Potential Other Applications for Linac QA

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dosimetric Leaf Gap</td>
<td>Can check along one or two dimensions.</td>
</tr>
<tr>
<td>3D Plan Delivery Constancy</td>
<td>“All in one” plan with all energies and multiple accessories for machine QA and upgrade testing.</td>
</tr>
<tr>
<td>IMRT Plan Delivery Constancy</td>
<td>A reference plan for machine QA and upgrade testing.</td>
</tr>
<tr>
<td>VMAT Plan Delivery Constancy</td>
<td>A reference plan for machine QA and upgrade testing.</td>
</tr>
<tr>
<td>Backup Daily QA</td>
<td>Every facility needs a daily QA backup</td>
</tr>
<tr>
<td>Energy Constancy</td>
<td>Enables the use of different metrics for energy and not just PDD or TMR.</td>
</tr>
</tbody>
</table>
Post Repair Testing

Do you break out the scanning water phantom if one energy is steered?

When a simple repair takes hours, and the machine has been partially disassembled, do you set up the scanning water phantom?
3. Linac QA with Arrays

Representative validation guidelines from Varian Medical Systems

<table>
<thead>
<tr>
<th>Axes Calibrations</th>
<th>True Beam</th>
<th>Beam Quality Assurance Guidelines for Axis Alignments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Calibration (no parts replaced)</td>
<td>✔️ ✔️</td>
<td>✔️ ✔️ ✔️</td>
</tr>
<tr>
<td>ENSW Calibration (no parts replaced)</td>
<td>✔️</td>
<td>✔️ ✔️ ✔️ ✔️</td>
</tr>
<tr>
<td>Ion Chamber Calibration (no parts replaced)</td>
<td>✔️ ✔️</td>
<td>✔️ ✔️ ✔️ ✔️</td>
</tr>
<tr>
<td>Carousel Transverse Calibration (no parts replaced)</td>
<td>✔️ ✔️</td>
<td>✔️ ✔️ ✔️ ✔️</td>
</tr>
<tr>
<td>Carousel Radial Calibration (no parts replaced)</td>
<td>✔️ ✔️</td>
<td>✔️ ✔️ ✔️ ✔️</td>
</tr>
<tr>
<td>MLC Calibration (See MLC Table Below)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After a service repair, the customer must be informed of the required QA checks listed in this document. Items labeled [QA] may be verified by either the Varian CSR or the customer. All final QA data must be approved by the customer. Dose calibration is the customer’s responsibility. Varian employees should not adjust Dose Calibration.
Choose the best statement that completes the following sentence: When measuring dynamic wedges for commissioning purposes...

1. a scanning water phantom must be used by the qualified medical physicist
2. either ion chamber or diode arrays can be used.
3. radiochromic film dosimetry lacks the necessary dynamic range.
4. 2D arrays should never be used.
Choose the best statement that completes the following sentence: When measuring dynamic wedges for commissioning purposes...

1. a scanning water phantom must be used by the qualified medical physicist
2. either ion chamber or diode arrays can be used.
3. radiochromic film dosimetry lacks the necessary dynamic range.
4. 2D arrays should never be used.

Answer is 2

4. Constancy Tests

After we have validated the performance of our array and properly commissioned our linac, how do we set up constancy tests using the array?

An example methodology in the context of TG-142 annual testing is provided.
## 4. Constancy Tests

### TG142 Annual Photon Sample Tests

<table>
<thead>
<tr>
<th>Annual Test</th>
<th>Sample Setup</th>
<th>Cumulative Fields per Photon E</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray Flatness Change from Baseline</td>
<td>30 x 30 cm field, 5 cm and 20 cm depths, <em>if needed reduce SSD to achieve field size</em></td>
<td>2</td>
</tr>
<tr>
<td>X-ray Symmetry Change from Baseline</td>
<td><em>Same as above</em></td>
<td>2 + 0 = 2</td>
</tr>
</tbody>
</table>

2/15/2016 Ritter 2D Arrays
## 4. Constancy Tests

**TG142 Annual Photon Sample Tests**

<table>
<thead>
<tr>
<th>Annual Test</th>
<th>Sample Setup</th>
<th>Cumulative Fields per Photon E</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Field Size Dependent Photon Output Factors</strong> <em>(measure the output and can acquire profile for reference)</em></td>
<td><strong>2 x 2 cm, 7 x 7 cm, 10 x 10 (ref), 20 x 5 cm, 30 x 30 cm fields, 10 cm depth</strong> <em>(field centered on detector, w/ detector appropriate for smallest field size)</em></td>
<td>5 + 2 = 7</td>
</tr>
<tr>
<td><strong>Physical Wedge Factor Constancy</strong></td>
<td>15 x 15 cm field, 10 cm depth</td>
<td>7 + 4 = 11</td>
</tr>
</tbody>
</table>
## 4. Constancy Tests

### TG142 Annual Photon Sample Tests

<table>
<thead>
<tr>
<th>Annual Test</th>
<th>Sample Setup</th>
<th>Cumulative Fields per Photon E</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray MU Linearity</td>
<td>15 x 15 cm field, 10 cm depth, <strong>Test 2 to 400 monitor units, 8 steps</strong></td>
<td>11 + 8 = 19</td>
</tr>
<tr>
<td>X-ray Output Constancy vs Dose Rate</td>
<td>15 x 15 cm field, 10 cm depth, <strong>Test min to max dose rate, 3 steps</strong></td>
<td>19 + 3 = 22</td>
</tr>
</tbody>
</table>
4. Constancy Tests

**TG142 Annual Photon Sample Tests**

<table>
<thead>
<tr>
<th>Annual Test</th>
<th>Sample Setup</th>
<th>Cumulative Fields per Photon E</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray Output Constancy vs Gantry Angle</td>
<td>30 x 30 cm field, approx. Dmax depth <em>Mount array on gantry and test at cardinal angles</em></td>
<td>22 + 4 = 26</td>
</tr>
<tr>
<td>X-ray Off Axis Factor vs Gantry Angle</td>
<td>Same as above. Analyze 2D dose and/or profiles.</td>
<td>26</td>
</tr>
</tbody>
</table>
# 4. Constancy Tests

## TG142 Annual Photon Sample Tests

<table>
<thead>
<tr>
<th>Annual Test</th>
<th>Sample Setup</th>
<th>Cumulative Fields per Photon E</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLC Transmission</td>
<td>15 x 15 cm field, 10 cm depth. Measure transmission through each bank + open field.</td>
<td>26 + 3 = 29</td>
</tr>
<tr>
<td>Dynamic Wedge Checks</td>
<td>20 x 20 EDW60IN and 15 x 10 off axis EDW30OUT, 10 cm depth</td>
<td>29 + 2 = 31</td>
</tr>
</tbody>
</table>
TG142 Annual Photon Sample Test Set
- Accomplishes majority of dosimetry portion.
- 31 measurements per energy, assuming both physical and dynamic wedges.
- Only 4 setup configurations are needed.
- Note that 16 of the measurements are dose to a single chamber, but using the array saves setup time and gives you planar data for further analysis if needed.
4. Constancy Tests

Setting up precision constancy tests:
1. Use the same water equivalent plastic plates in the same orientation and position each time (label and orient each).
2. Use the same backscatter each time.
4. Constancy Tests

Setting up precision constancy tests:

3. Carefully align and level the array. Imaging or a precision field can be used for alignment.

- The MLC “cross” shape captures the two central rows and two central columns of detectors
- Align to achieve a uniform dose along the two adjacent rows and columns
4. Constancy Tests

Setting up precision constancy tests:

4. Deliver a large uniform photon field to your array and look for detector inconsistencies before you perform any measurements.
4. Constancy Tests

5. Consider custom action/investigation levels and trend track results.

A constancy check with careful baselines may allow action levels < TG-142 tolerances.

This example demonstrates investigation levels of 0.8 % vs the 2% TG-142 tolerance.
5. Examples

Example 1: Photon Energy Check

A method to replace TPR/PDD measurements with a metrics for beam flatness.


5. Examples

Example 1: Photon Energy Check

Use the metric $F_{DN}$, the diagonal normalized flatness.

$$F_{DN} = \frac{\left( \sum_{i=1}^{4} R_{d}^{i} \right) / 4}{R_{CAX}} \times 100,$$

where $R_{d}^{i}$ are the readings of the diagonal ion chambers and $R_{CAX}$ is the reading of the CAX ion chamber. In this study, we used the diagonal chambers at 17.7 cm from center.

5. Examples

**Example 1: Photon Energy Check**

Bend magnet current was changed to simulate an $E$ change. **The blue line shows the sensitivity of $F_{DN}$ at 18MV. The red and black lines are for PDD.**

Which of the following statements regarding metrics for assessing changes in photon beam energy is correct?

1. Percent depth dose (PDD) at 10 cm is best for detecting increases and decreases in energy.
2. Flatness metrics are more sensitive than PDD for detecting increases and decreases in energy.
3. PDD is more sensitive to increases in beam energy while flatness is more sensitive to decreases.
4. PDD is more sensitive to decreases in energy while flatness is more sensitive to increases.
Which of the following statements regarding metrics for assessing changes in photon beam energy is correct?

1. Percent depth dose (PDD) at 10 cm is best for detecting increases and decreases in energy.

2. Flatness metrics are more sensitive than PDD for detecting increases and decreases in energy.

3. PDD is more sensitive to increases in beam energy while flatness is more sensitive to decreases.

4. PDD is more sensitive to decreases in energy while flatness is more sensitive to increases.

5. Examples

Example 2: Dosimetric Leaf Gap (DLG)
2. Rangel and Dunscombe (2009) showed that a systematic 0.3mm MLC gap error can correlate to a 2% EUD deviation for dynamic IMRT delivery.
3. You can easily implement a measurement of DLG in 2D using a planar array.
4. Place the array at a source-to-detector distance that matches MLC leaves to a row of detectors.
Example 2: DLG measured with a 2D array.

Target is 1.05 mm

Values outside 0.9 mm to 1.2 mm are flagged yellow

<table>
<thead>
<tr>
<th>Leaf Pair</th>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>Section 4</th>
<th>Section 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>-1.01</td>
<td>-1.01</td>
<td>-1.01</td>
<td>-0.99</td>
<td>-0.99</td>
</tr>
<tr>
<td>18</td>
<td>-1.04</td>
<td>-1.02</td>
<td>-1.02</td>
<td>-0.98</td>
<td>-0.97</td>
</tr>
<tr>
<td>19</td>
<td>-0.97</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td></td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>35</td>
<td>-0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>-0.99</td>
<td>-1.00</td>
<td>-0.99</td>
<td>-0.98</td>
<td>-0.97</td>
</tr>
<tr>
<td>37</td>
<td>-0.97</td>
<td>-0.96</td>
<td>-0.97</td>
<td>-0.95</td>
<td>-0.94</td>
</tr>
<tr>
<td>38</td>
<td>-0.93</td>
<td>-0.93</td>
<td>-0.93</td>
<td>-0.93</td>
<td>-0.92</td>
</tr>
<tr>
<td>39</td>
<td>-0.74</td>
<td>-0.73</td>
<td>-0.72</td>
<td>-0.70</td>
<td>-0.69</td>
</tr>
<tr>
<td>40</td>
<td>-0.99</td>
<td>-0.97</td>
<td>-0.98</td>
<td>-0.95</td>
<td>-0.94</td>
</tr>
<tr>
<td>41</td>
<td>-0.90</td>
<td>-0.89</td>
<td>-0.89</td>
<td>-0.88</td>
<td>-0.86</td>
</tr>
<tr>
<td>42</td>
<td>-1.01</td>
<td>-1.01</td>
<td>-1.02</td>
<td>-1.01</td>
<td>-1.00</td>
</tr>
<tr>
<td>43</td>
<td>-1.01</td>
<td>-1.01</td>
<td>-1.01</td>
<td>-1.01</td>
<td>-1.01</td>
</tr>
</tbody>
</table>

Leaf #39 deliberate 0.3 mm error
Leaf #41 slightly out of desired range
Example 3: Detecting subtle linac differences.

A great deal of information is acquired when you measure fields with arrays. What do you focus on?

Beyer’s work (JACMP 2013) comparing different Varian accelerators gives us a good starting point.

Consider extremes of field sizes, large distances off axis, shallow (and deep?) depths, and penumbra.
5. Examples

Example 3: Detecting subtle linac differences.

Used a 14 field test plan to compare Varian TrueBeams and a 21EX, machines calibrated identically, 10x10 PDDs within 0.2%.

Small fields, shallow depths off axis, penumbra, and the collimator exchange effect were sensitive beam property indicators...but you had to look close!

5. Examples

Example 3: Detecting subtle linac differences.

Differences were mild, use action levels < 1%.

34 x 34 cm field at reduced SSD and 1 cm depth

21EX vs TrueBeam

TrueBeam vs TrueBeam

Planar dose difference map set to show 1% dev in red

Radial profile

TrueBeam 1 in red
21EX in green

Radial profile

TrueBeam 1 in red
TrueBeam 2 in green

2/15/2016
MPPG 5 describes essential treatment planning system quality assurance.

A majority of the tests can be efficiently performed with arrays, and the report specifically endorses their use.

6. TG 244 Applications

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4</td>
<td>Small MLC-shaped field (non SRS)</td>
</tr>
<tr>
<td>5.5</td>
<td>Large MLC-shaped field with extensive blocking (e.g., mantle)</td>
</tr>
<tr>
<td>5.6</td>
<td>Off-axis MLC shaped field, with maximum allowed leaf over travel</td>
</tr>
<tr>
<td>5.7</td>
<td>Asymmetric field at minimal anticipated SSD</td>
</tr>
<tr>
<td>5.8</td>
<td>10×10 cm² field at oblique incidence (at least 20°)</td>
</tr>
<tr>
<td>5.9</td>
<td>Large (&gt; 15 cm) field for each nonphysical wedge angle</td>
</tr>
</tbody>
</table>

This can be tested at larger angles if done in solid phantom. Test 5.9 is specific to nonphysical wedges. For all tests, measurements in the high-dose region, penumbra, and low-dose tail regions should be compared to calculated values at various depths (including slightly beyond \( d_{\text{max}} \), midrange/10–15 cm, and deep/25–30 cm) and off-axis positions. Table 5 summarizes the

6. TG 244 Applications

Commercial array software may be especially amenable to analysis of the planar results.

**Table 5. Basic TPS photon beam evaluation methods and tolerances.**

<table>
<thead>
<tr>
<th>Region</th>
<th>Evaluation Method</th>
<th>Tolerancea (consistent with IROC Houston)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High dose</td>
<td>Relative dose with one parameter change from reference conditions</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Relative dose with multiple parameter changesb</td>
<td>5%</td>
</tr>
<tr>
<td>Penumbra</td>
<td>Distance to agreement</td>
<td>3 mm</td>
</tr>
<tr>
<td>Low-dose tail</td>
<td>Up to 5 cm from field edge</td>
<td>3% of maximum field dose</td>
</tr>
</tbody>
</table>

a Tolerances are relative to local dose unless otherwise noted.
b For example, off-axis with physical wedge.

6. TG 244 Applications

Examples of TG-244 Testing:

Test 5.5

Measured dose dbn

Radial Profile
Measured in red
Calculated in green

Planar dose difference map set to show 2% dev in red

Calculated dose dbn
7. Limitations

What are some of the challenges and limitations with using arrays?

1. Depth dose: Can acquire planes at different depths but depth dose scans are still required.

2. Spatial density / resolution in steep dose gradient regions (such as penumbra). Apply appropriate interpolation for IMRT/VMAT plans (Feygelman, Stathakis talks) or use other methods with higher resolution.
3. Potential non-linearities and energy dependence due to detector response effects, incomplete frame capture, saturation of the electronics, etc.

4. Detector-to-detector differences can hide subtle changes.

5. Field size limitations.

6. Use of water equivalent plastics.
The report of task group 142 on quality assurance of medical accelerators conveys which of the following:

1. Arrays are only suitable for daily QA.

2. Arrays are only suitable for monthly QA.

3. The QMP should scan the beam using a scanning water phantom at intervals not to exceed 14 months.

4. The proper measurement tools should be chosen by matching the detectors and software to the needs and sensitivity requirements.
The report of task group 142 on quality assurance of medical accelerators conveys which of the following:

1. Arrays are only suitable for daily QA.
2. Arrays are only suitable for monthly QA.
3. The QMP should scan the beam using a scanning water phantom at intervals not to exceed 14 months.
4. The proper measurement tools should be chosen by matching the detectors and software to the needs and sensitivity requirements.

**Answer is 4**

Perform a complete commissioning of any array you want to use.

Once you have commissioned your linac and array system you can set up constancy tests and acquire baselines.

Understand the limitations of your system and when you need to resort to other tests.
Thank you for your attention!