VMAT
Dosimetric characteristics and delivery
Marta Paiusco
Agenda

- IMAT Milestones
- Planning systems
- Commissioning
Milestone

Arc Therapy is a very old concept

**Dynamic Arc therapy** ≡ **Conformal arc therapy**

beams aperture is dynamically shaped by the MLC to match the beam’s eye view of the target

1983 **A theory by L.M. Chin**

- gantry rotation (simulated by 72 static fields) +
- collimator motion (conformed to the target) +
- dose rate variation (different field’s weight)

highly improve conformal dose distribution
Brahme 1988: Fluence Intensity Modulation concept
Mackie 1993: Tomotherapy
Cedric X Yu 1995 IMAT: an alternative to Tomotherapy

Tomotherapy vs IMAT

continuous gantry rotation
fan beam
binary collimator
couch translation

continuous gantry rotation
cone beam
standard MLC
couch fixed

Shepard 1999: dosimetric advantages of rotational treatments
The benefits of IMRT are most apparent with the complex target shape. IMRT can provide both sparing of the regions at a risk and dose uniformity in the target. Segmented fields (IMAT) can provide a significant sparing of sensitive structures located in close proximity to the target, but IMRT provides the ability to provide tight contours matching the tumor shape.
Planning parameters: collimator size and number of fields

Table II. Dependence upon collimator size using diverging pencil beams.

<table>
<thead>
<tr>
<th>Collimator size (mm)</th>
<th>Standard deviation in dose over the target</th>
<th>Mean dose region at its</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.090</td>
<td>0.553</td>
</tr>
<tr>
<td>10</td>
<td>0.079</td>
<td>0.283</td>
</tr>
<tr>
<td>6</td>
<td>0.059</td>
<td>0.190</td>
</tr>
<tr>
<td>4</td>
<td>0.048</td>
<td>0.180</td>
</tr>
<tr>
<td>2</td>
<td>0.040</td>
<td>0.156</td>
</tr>
</tbody>
</table>

Table III. Dependence upon the number of angles.

<table>
<thead>
<tr>
<th>Number of angles</th>
<th>Standard deviation in dose over target</th>
<th>Minimum target dose</th>
<th>Mean dose to RAR</th>
<th>Treatment time</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.124</td>
<td>0.644</td>
<td>0.488</td>
<td>27</td>
</tr>
<tr>
<td>5</td>
<td>0.090</td>
<td>0.666</td>
<td>0.215</td>
<td>25</td>
</tr>
<tr>
<td>7</td>
<td>0.064</td>
<td>0.797</td>
<td>0.206</td>
<td>25</td>
</tr>
<tr>
<td>9</td>
<td>0.064</td>
<td>0.772</td>
<td>0.192</td>
<td>25</td>
</tr>
<tr>
<td>11</td>
<td>0.058</td>
<td>0.775</td>
<td>0.186</td>
<td>25</td>
</tr>
<tr>
<td>15</td>
<td>0.053</td>
<td>0.710</td>
<td>0.180</td>
<td>25</td>
</tr>
<tr>
<td>21</td>
<td>0.049</td>
<td>0.768</td>
<td>0.171</td>
<td>25</td>
</tr>
<tr>
<td>33</td>
<td>0.038</td>
<td>0.809</td>
<td>0.155</td>
<td>25</td>
</tr>
</tbody>
</table>
Cedric X Yu idea:

- IMRT: N fields with M Intensity level
- hp: Plan Quality PQ = f(NxM)
- Th: Increasing the number of gantry angle we can reduce the number of intensity level

The idea is to share the field modulation with several neighboring segments and regain the modulation through the superposition of these fields or arcs

S&S = IMRT 7 fields with 11 Intensity level ⇒ 78 gantry angle should be enough for the same PQ without intensity modulation

A single arc with a sufficient number of aperture shape variations would be able to create optimal treatment plans

The idea is a Multi-arc therapy with NO Modulation inside the field
Intensity Modulated Arc Therapy

**Arc therapy**: depict the actual delivery method  
(gantry moves continuously while the beam is on)

**Intensity modulated**: No intensity modulation is within each beam  
The needed intensity variation at the target region is achieved with the aperture from the neighboring angles.

2008 Otto K. developed a single arc IMAT with variable dose rate

**Volumetric Modulated Arc Therapy**  (Varian :RapidArc™- Elekta VMAT™)
IMAT Planning- Inverse planning solutions

• Varian : Eclipse RapidArc
• Philips: Pinnacle SmartArc
• Elekta: Monaco VMAT & Oncentra MasterPlan VMAT
• Raysearch : VMAT module
Main problem:

**Aperture connectivity**
To make the plan deliverable, MLC cannot travel long distance while the gantry rotates around the patient and the radiation beam is on. Geometric connectivity between adjacent beam angles must be satisfied.

**Gantry rotation speed**
cannot have frequent variations due to its weight so variations in aperture weights must be achieved primarily by dose rate variations.
IMAT Planning- Inverse planning solutions

• Pinnacle, Masterplan and Raysearch system
• Two step process based on Bzdusek approche

STEPS:

1. Set arc parameters
2. Generate initial arc (fields per arc)
3. Optimize the fluence and aperture for all the beam used to approximating an arc without constraints related to the delivery.
4. Apertures are spaced over the angular arc range and e DAO algorithm is used to optimize weights and shapes taking into account MLC and converting the beam intensities and aperture into deliverable MLC segments
IMAT Planning- Inverse planning solutions

**Eclipse RapidArc**

**One step inverse planning algorithm**

Based on Otto paper where Shepard _Direct Aperture Optimization_ approach

1. Based on more control points in a single arc (177)
2. Progressive sampling was used to improve the speed of the algorithm.
3. All the delivery constraints are included directly into the IMAT DAO optimization.
4. A simulated annealing algorithm is used to optimize the MLC leaf positions and aperture weights.
5. After each change in an MLC leaf position, the algorithm checks the delivery constraints
• Plans comparison

IMRT

VMAT 1 arc

VMAT 2 arcs
<table>
<thead>
<tr>
<th>Paper [ref]</th>
<th>VMAT commercial system</th>
<th>Number of patients</th>
<th>Site and dose</th>
<th>Comparison</th>
<th>PTV</th>
<th>OAR</th>
<th>MU per fraction</th>
<th>Treatment time per fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palma et al [51]</td>
<td>Predecessor to RapidArc</td>
<td>10</td>
<td>Prostate alone 74 Gy in 37 fractions</td>
<td>3D-CRT vs IMRT(5F,SW) vs CDR-VMAT (SA) vs VDR-VMAT (SA)</td>
<td>IMRT and VMAT – similar PTV coverage and homogeneity (heterogeneity inferior to 3D-CRT). Conformity best with IMRT and VDR-VMAT</td>
<td>VDR-VMAT best (compared with IMRT for sparing of rectum and femoral heads; compared with CDR-VMAT for sparing of bladder and rectum)</td>
<td>CDR-VMAT, 491.6; VDR-VMAT, 454.2; IMRT, 788.8; 3D-CRT, 295.5</td>
<td>VMAT, 1 min; IMRT, 5 min</td>
</tr>
<tr>
<td>Zhang et al [52]</td>
<td></td>
<td>11</td>
<td>Prostate + proximal SV 86.4 Gy</td>
<td>IMRT (5F,SS) vs VMAT (SA)</td>
<td>IMRT – slightly higher dose to PTV (95%, D95%, mean dose and TCP) and better homogeneity compared with VMAT</td>
<td>VMAT better then IMRT (sparing of rectum, bladder, femoral heads)</td>
<td>VMAT, 290; IMRT, 642</td>
<td></td>
</tr>
<tr>
<td>Kjaer-Kristoffersen et al [53]</td>
<td>RapidArc</td>
<td>8</td>
<td>Prostate + SV, 78 Gy (5 pts); 74 Gy (1 pt) Prostate bed, 66 Gy (2 pts)</td>
<td>IMRT (5F,SW) vs VMAT (partial SA)</td>
<td>IMRT – slightly better PTV coverage (V95%) but VMAT better in PTV minus rectum coverage. Hotspots higher in VMAT plans.</td>
<td>VMAT better than IMRT (sparing of bladder, rectum). Integral dose to body similar. Low dose bath (5 Gy) to body larger for IMRT</td>
<td>VMAT, 529; IMRT, 647</td>
<td></td>
</tr>
<tr>
<td>Hardcastle et al [54]</td>
<td>SmartArc</td>
<td>10</td>
<td>Prostate 78 Gy in 39 fractions</td>
<td>IMRT (7F,SS) vs VMAT (SA)</td>
<td>IMRT and VMAT – similar PTV coverage (except D95% where VMAT had lower values).</td>
<td>VMAT better than IMRT at rectal sparing at doses &lt;50 Gy. VMAT – higher doses to femoral heads. No significant difference in bladder doses.</td>
<td>VMAT, 417; IMRT, 526</td>
<td>VMAT, 1.3 min; IMRT, 4.5 min</td>
</tr>
<tr>
<td>Ost et al [55]</td>
<td></td>
<td>12</td>
<td>Prostate + SV (76 Gy) and IPL boost (82 Gy). Additional IPL dose level &gt;85 Gy</td>
<td>IMRT (3F,5F,7F,5S) vs VMAT (SA)</td>
<td>IMRT (5F,7F) and VMAT – similar PTV coverage and all better than IMRT 3F. Dose escalation up to 95 Gy to IPL with VMAT</td>
<td>VMAT better at rectal sparing (significant at rectal volumes receiving 20–50 Gy). No difference in integral dose to body.</td>
<td>For 6 MV: VMAT, 447; IMRT (3F), 362; IMRT (5F), 407; IMRT (7F), 434</td>
<td>VMAT, 1.95 min; IMRT (5F), 3.85 min; IMRT (7F), 4.82 min</td>
</tr>
<tr>
<td>Weber et al [56]</td>
<td>RapidArc</td>
<td>7</td>
<td>Recurrent prostate carcinoma 56 Gy in 14 fractions</td>
<td>IMRT (5F,SW) vs IMPT vs VMAT (SA)</td>
<td>IMPT best for PTV coverage, VMAT better than IMRT for GTV and PTV coverage. VMAT (high definition MLC) – best for homogeneity. IMRT, VMAT better than IMPT for conformity</td>
<td>IMPT and RA better than VMAT (sparking of rectum, urethra, bladder). Integral doses to body lowest with IMPT. IMPT best at sparing penile bulb</td>
<td>VMAT, 1,95 min; IMRT (5F), 3.85 min; IMRT (7F), 4.82 min</td>
<td></td>
</tr>
<tr>
<td>Kopp et al [57]</td>
<td>RapidArc</td>
<td>292</td>
<td>Prostate 77.4 Gy in 43 fraction</td>
<td>IMRT (7F,SW) vs VMAT (SA)</td>
<td>IMRT and VMAT similar PTV coverage (VMAT less homogeneous). VMAT – slightly higher D2%</td>
<td>VMAT better than IMRT (sparing of rectum at high doses, bladder, femoral heads, penile bulb)</td>
<td>Primary plans: VMAT (SA), 429; VMAT (DA), 444; IMRT, 1300. Boost plans: VMAT (SA), 443; VMAT (DA), 484; IMRT, 777</td>
<td>Primary plans: VMAT (SA), 1.5 min; VMAT (DA), 3.1 min; IMRT, 8.1 min. Boost plans: VMAT (SA), 1.5 min; VMAT (DA), 3.1 min; IMRT, 4.9 min</td>
</tr>
<tr>
<td>Yoo et al [58]</td>
<td>RapidArc</td>
<td>10</td>
<td>Prostate, SV and LN (primary) 46.8 Gy; prostate and SV (boost) 28.8 Gy (1.8 Gy per fraction)</td>
<td>IMRT (9F,7F) vs VMAT (SA) vs VMAT (DA)</td>
<td>Primary plans– IMRT better than VMAT (PTV coverage, conformity). Boost plans – similar PTV coverage, homogeneity; IMRT had worse conformity compared to VMAT</td>
<td>Primary plans–IMRT better than VMAT (sparing of bladder, rectum, small bowel). Boost plans – IMRT and DA VMAT better than SA VMAT. Higher integral doses to body with VMAT</td>
<td>Primary plans: VMAT (SA), 429; VMAT (DA), 444; IMRT, 1300. Boost plans: VMAT (SA), 443; VMAT (DA), 484; IMRT, 777</td>
<td>Primary plans: VMAT (SA), 1.5 min; VMAT (DA), 3.1 min; IMRT, 8.1 min. Boost plans: VMAT (SA), 1.5 min; VMAT (DA), 3.1 min; IMRT, 4.9 min</td>
</tr>
<tr>
<td>Reference</td>
<td>Patient</td>
<td>Tumour Site</td>
<td>Comparison</td>
<td>PTV</td>
<td>OAR</td>
<td>MU per fraction</td>
<td>Treatment time per fraction</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>---------</td>
<td>-------------</td>
<td>------------</td>
<td>-----</td>
<td>-----</td>
<td>----------------</td>
<td>-----------------------------</td>
<td></td>
</tr>
<tr>
<td>Van de Riet et al. [91]</td>
<td>RapidArc</td>
<td>Nasopharynx, oropharynx and hypopharynx</td>
<td>IMRT (7F, SW) vs VMAT (SA) vs VMAT (DA)</td>
<td>Similar PTV coverage. DA VMAT better than SA VMAT and IMRT for homogeneity</td>
<td>No significant difference. Parotid dose lower with DA VMAT (by average 2Gy) compared with SA VMAT and IMRT</td>
<td>VMAT (SA), 439; VMAT (DA), 458; IMRT, 1108</td>
<td>VMAT (SA), 463; VMAT (DA), 584; IMRT, 1126</td>
<td></td>
</tr>
<tr>
<td>Riet et al. [92]</td>
<td>RapidArc</td>
<td>Oropharynx, hypopharynx and larynx</td>
<td>IMRT (7–9F, SW) vs VMAT (SA) vs VMAT (DA)</td>
<td>Similar PTV coverage and conformity. DA VMAT better than SA VMAT and IMRT for homogeneity (SA VMAT slightly inferior to IMRT)</td>
<td>VMAT better than IMRT at sparing spinal cord (D2%, mean dose), brainstem (D25%, mean dose) and parotid glands (mean dose). DA VMAT better than SA VMAT. VMAT — lower integral doses to body.</td>
<td>VMAT (SA), 463; VMAT (DA), 584; IMRT, 1126</td>
<td>VMAT (SA), 1.2–1.5 min; VMAT (DA), 3 min; IMRT, 15 min</td>
<td></td>
</tr>
<tr>
<td>Johnston et al. [93]</td>
<td>RapidArc</td>
<td>Nasopharynx and oropharynx</td>
<td>IMRT (9F, SW) vs VMAT (DA)</td>
<td>Similar PTV coverage IMRT slightly better than VMAT for conformity and homogeneity</td>
<td>No significant differences for spinal cord, brainstem doses. VMAT better than IMRT for contralateral parotid gland sparing.</td>
<td>VMAT, 529; IMRT, 1628</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kuczek et al. [94]</td>
<td>SmartArc</td>
<td>Post-operative pharynx/larynx, primary pharynx, paranasal sinus</td>
<td>IMRT (9F, SS) vs VMAT (1–3 arcs)</td>
<td>For PTV coverage and homogeneity: (post-operative pharynx/larynx) SA VMAT inferior to IMRT, DA VMAT = IMRT; TA VMAT better than IMRT; (primary pharynx) SA and DA VMAT inferior to IMRT TA VMAT = IMRT; (paranasal sinus) All VMAT plans inferior to IMRT; (decreased coverage between orbits)</td>
<td>(Post-operative pharynx/larynx, primary pharynx) No significant difference (SA VMAT inferior to DA VMAT; TA VMAT and IMRT) (paranasal sinus) All VMAT plans inferior to IMRT for lens sparing</td>
<td>IMRT, 430–688; VMAT (SA), 358–440; VMAT (DA), 460–519; VMAT (TA), 506–560</td>
<td>IMRT, 9.55–12.25 min; VMAT (SA), 1.85–2 min; VMAT (DA), 3.83–3.98 min; VMAT (TA), 4.42–4.58 min</td>
<td></td>
</tr>
<tr>
<td>Zertelsen et al. [95]</td>
<td>SmartArc</td>
<td>Nasopharynx and hypopharynx</td>
<td>IMRT (5–7F, SS) vs VMAT (SA)</td>
<td>Similar PTV coverage and homogeneity. VMAT better than IMRT for elective PTV coverage and conformity</td>
<td>VMAT better than IMRT at sparing spinal cord, parotid glands, submandibular glands at high dose levels. VMAT — lower volumes of normal tissue (outside PTV) irradiated to higher doses IMRT and DA VMAT largely similar OAR sparing (SA VMAT inferior to IMRT and DA VMAT)</td>
<td>VMAT, 460; IMRT, 503</td>
<td>VMAT, 4.02 min; IMRT, 6.2 min</td>
<td></td>
</tr>
<tr>
<td>Varela-Moret et al. [96]</td>
<td>Oncentra Masterplan</td>
<td>Oral cavity, hypopharynx, nasal cavity</td>
<td>IMRT (7–9F, SS) vs VMAT (SA) vs VMAT (DA)</td>
<td>IMRT and DA VMAT similar PTV coverage, homogeneity (SA VMAT inferior to IMRT and DA VMAT)</td>
<td>IMRT and DA VMAT largely similar OAR sparing (SA VMAT inferior to IMRT and DA VMAT)</td>
<td>VMAT (SA), 491.3; VMAT (DA), 596.4; IMRT, 575.4</td>
<td>VMAT (SA), 1.86 min; VMAT (DA), 3.64 min; IMRT, 11.7 min</td>
<td></td>
</tr>
</tbody>
</table>
VMAT vs other techniques

It is important to note that there are many other issues in addition to plan quality that are associated with different delivery techniques. These include the efficiency of planning, delivery, quality assurance (QA), the complexity and reliability of delivery, and the total Mus required to deliver the prescribed doses and the total leakage radiation received by the patient outside the target region.

CX YU
VMAT Commissioning

Marta Paiusco
• Guidelines for commissioning
• TG 142
• TG 119

Basic requirements:

- Calculate doses must match the **delivered** ones
- Delivery must be stable and reproducible

We need to verify the reliability and accuracy of the whole chain from planning to delivery.
VMAT delivery requires more advanced linac control capabilities than IMRT

- Variable dose rate
- Variable gantry speed
- Dynamic MLC movement

Like IMRT for a TPS

- Geometric characteristics of the linac must be put into the planning system
- Geometrical errors in MLC positioning can have dose impact
- Tongue and groove modeling can have dosimetric impact

Dose calculation model from the fixed beams may not accurately reflect rotational delivery due to the lack of adequate sampling.

Commissioning and QA Program is closely related to the IMAT solution: Delivery and TPS
Commissioning by C C Ling : Linac capabilities

1. Accuracy of the DMLC during RapidArc : picket fence test
2. Ability to vary dose rate and grantry speed

the 7sQA plan, which delivered the same dose to the seven strips with different combinations of $\Delta \text{MU}/\Delta t$, $\Delta \theta$, and $\Delta \theta/\Delta t$: 111 MU/min, 90° and 5.54°/s; 222 MU/min, 45° and 5.54°/s; 332 MU/min, 30° and 5.54°/s; 443 MU/min, 22.5° and 5.54°/s; 554 MU/min, 18° and 5.54°/s; 600 MU/min, 15° and 5°/s; 600 MU/min, 12.9° and 4.3°/s.

3. Ability to accurately vary MLC leaf speed

four different parts were exposed to the same dose with the four sliding windows at leaf speeds of 0.46, 0.92, 1.84, and 2.76 cm/s. When the LSQA radiation profile was normalized to and superimposed on the profile of the corresponding open MLC field, the two profiles were closely matched.
RapidArc commissioning QA with Epiqa

Three tests (recommended by Ling et al [2] and adopted by Varian) were performed during the commissioning phase, and then repeated at least once a month for a total of 6 acquisitions. Analysis was performed with Epiqa. Results presented a very good stability of RapidArc delivery as dose rate variation, gantry speed and leaf speed.

T1: Picket Fence Test during RapidArc
T2: Control of Dose Rate and Gantry Speed during RapidArc
T3: Control of Leaf Speed during RapidArc
A. Van Esch: Additional commissioning and QA are required

Systematic method

A. Linac commissioning and QA
B. TPS validation
C. Patient QA
Linac Performances

Test 1: Dose is delivered only for a narrow angular sector.

Static MLC:
Dose less segmente gantry speed = max
Dose segmente gantry speed = min
To test acceleration and deceleration effects, inertially overly smoothened
Errors introduced 1° 2° 3°

Dynamic MLC: MLC sweeping motion at maximum speed at the start of narrow sector delivery leaves must be in a central positions
To test Synchronization from MLC and gantry
Errors introduces 0.2-0.5-1 mm

Introduced errors of 1° do not distort the measurements
To test the impact of gantry speed, gravity and inertia. High MU
Dose rate at maximum minimum gantry speed at 0°
dose maximum at 0°
like a double stairs
if a parameter affects the test we will see a broadening in a transition from one sector to another.

Interplay between gantry angle, MLC position and dose delivered
MLC gap of 1 cm
A narrow angular sector is delivered
The metal road with a sferical tip should be precisely in the centre of the gap.
MLC gap of 1 cm
A narrow angular sector is delivered
The metal road with a spherical tip should be precisely in the centre of the gap.

Errors of 1° in a gantry position are now detectable
TPS

Is the calculation done with the validated algorithm? 

YES

Is the calculation performed like in a validated delivery technique?

Dose calculation differs from the static ones as it makes use of an interpolation between two control points

Is the standard calibration methods proper?

Arc vs static field

Are the standard validation package representative of the typical VMAT configuration?

Small field in a large collimator opening
Small field off axis
MLC tips nearly closed
<table>
<thead>
<tr>
<th>Gantry and MLC</th>
<th>Collimator settings (cm)</th>
<th>HD MLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLG, central:</td>
<td>X=14, Y=24 (---)</td>
<td></td>
</tr>
<tr>
<td>DLG, off-axis:</td>
<td>X=1-2, X2=16, Y=24 (---)</td>
<td></td>
</tr>
<tr>
<td>OF, central:</td>
<td>X=4,4, Y=4,4,40</td>
<td></td>
</tr>
<tr>
<td>OF, off-axis:</td>
<td>X=1-2, X2=16, Y=4,4,20</td>
<td></td>
</tr>
<tr>
<td>X=14, Y=20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dynamic Gantry, TnG</th>
<th>G = 345 → 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>central: X=14, Y=20</td>
<td></td>
</tr>
<tr>
<td>X=14, Y=24 (---)</td>
<td></td>
</tr>
<tr>
<td>X=1-2, X2=16, Y=24 (---)</td>
<td></td>
</tr>
</tbody>
</table>

Dynamic Twinkle G = 200 → 160

Ganrise G = 200 → 160

\( \delta = 20 \text{ mm} \)
Commissioning of TPS to check the impact of different parameters

Control point resolution = interpolation between two control point

dynamic Gantry, dynamic MLC: sweeping gap
$G = 345 \rightarrow 15$

$\delta = 20 \text{ mm}$
AAPM TG-119 IMRT commissioning like

Test plans verification

Dosimeter must be tested, validated and its sensitivity must be known
The AAPM TG-142 report recommended that the tolerance of laser localization was 1.5 mm for IMRT.\(^{(32)}\) For both ArcCHECK and Delta\(^4\) systems, 1° rotational error could cause an approximate error of 2 mm on the surface of the phantoms. Therefore, the cumulative effect of

We break down QA dosimeter validation into a logical process of three distinct phases (I-III). In Phase I testing, the ArcCHECK exhibited robust response uniformity between the diodes. Measurement accuracy for the fields exceeding approximately 15 cm in width is compromised by the diodes’ angular response dependence. This is being addressed by the manufacturer. ArcCHECK exhibits stronger field size response dependence compared to its predecessor, MapCHECK, which should be corrected in the software.
A comparison of the gamma index analysis in various commercial IMRT/VMAT QA systems

Mohammad Hussein\textsuperscript{a,b,*}, Pejman Rowshanfarzad\textsuperscript{c}, Martin A. Ebert\textsuperscript{c,d}, Andrew Nisbet\textsuperscript{a,b}, Catharine H. Clark\textsuperscript{a,e}

Table 1
Summary of the mean and minimum measured gamma index passing criteria for each system. The concordance correlation coefficient, $\rho_c$, is also given assessing agreement with independent gamma index. The softwares are listed in the same order as the associated measurement system.

<table>
<thead>
<tr>
<th>System</th>
<th>% Detectors/pixels passing with $\gamma &lt; 1$ and $\rho_c$</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3%/3 mm</td>
<td>3%/2 mm</td>
<td>2%/2 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Min</td>
<td>$\rho_c$</td>
<td>Mean</td>
<td>Min</td>
<td>$\rho_c$</td>
<td>Mean</td>
<td>Min</td>
</tr>
<tr>
<td>Software predicted</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verisoft v5</td>
<td>99.0</td>
<td>89.9</td>
<td>0.97</td>
<td></td>
<td>98.4</td>
<td>83.9</td>
<td>0.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SNC Patient v6</td>
<td>98.7</td>
<td>84.5</td>
<td>0.97</td>
<td></td>
<td>98.0</td>
<td>78.5</td>
<td>0.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta4 software</td>
<td>98.8</td>
<td>89.4</td>
<td>0.96</td>
<td></td>
<td>98.3</td>
<td>84.9</td>
<td>0.93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OmniPro IMRT v7</td>
<td>98.7</td>
<td>82.6</td>
<td>0.95</td>
<td></td>
<td>97.9</td>
<td>73.8</td>
<td>0.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Portal Dosimetry v10</td>
<td>98.7</td>
<td>84.7</td>
<td>0.97</td>
<td></td>
<td>98.0</td>
<td>73.6</td>
<td>0.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Independent predicted</td>
<td>98.8</td>
<td>87.0</td>
<td></td>
<td></td>
<td>97.9</td>
<td>78.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PTW 2D-Array</td>
<td>98.0</td>
<td>86.3</td>
<td>0.87</td>
<td></td>
<td>96.2</td>
<td>79.3</td>
<td>0.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ArcCHECK</td>
<td>98.4</td>
<td>87.2</td>
<td>0.96</td>
<td></td>
<td>97.2</td>
<td>81.6</td>
<td>0.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta4</td>
<td>96.2</td>
<td>86.6</td>
<td>0.53</td>
<td></td>
<td>93.4</td>
<td>78.5</td>
<td>0.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gafchromic</td>
<td>98.1</td>
<td>88.2</td>
<td>0.81</td>
<td></td>
<td>94.6</td>
<td>76.5</td>
<td>0.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPID</td>
<td>97.7</td>
<td>77.4</td>
<td>0.82</td>
<td></td>
<td>96.2</td>
<td>66.3</td>
<td>0.84</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Open problems

Gamma Passing rate criteria is dosimeter independent?

3%3mm criteria is suggested by TG119: insensitive to most of the errors! 2%2mm and local normalization should be better.

90% -95% mode than 95% ??? The best threshold

The AAPM TG-142 report recommended that the tolerance of laser localization was 1.5 mm for IMRT.\(^{(32)}\) For both ArcCHECK and Delta\(^4\) systems, 1° rotational error could cause an approximate error of 2 mm on the surface of the phantoms. Therefore, the cumulative effect of

Patient Specific Metric (DVH) must be better than Gamma passing rate function
RapidArc more susceptible to delivery uncertainties than dynamic IMRT?

Gregory T. Betzel and Byong Yong Yi
Department of Radiation Oncology, University of Maryland School of Medicine, Baltimore, Maryland 21201

Fig. 4. Dose distribution comparisons using 2%-2 mm Gamma analysis criterion illustrating pass rates for MLC leaf bank shifts of 0.5, 1.0, 1.5, and 2.0 mm for (a) one HN case and (b) one prostate case. PTV contours are shown. Points that failed are indicated in red.

Fig. 5. Comparison of average PTV minimum, maximum and mean values for (a) head-and-neck and (b) prostate cases planned using either window (SW) IMRT or RapidArc (RA) cases with systematic gantry angle variations.
Results: There is a linear correlation of MLC errors with gEUD for all error types. The gEUD dose sensitivities with MLC error for the PTV70 were −0.2, −0.9, −2.8 and 1.9 Gy/mm for random, systematic shift, systematic close and systematic open MLC errors, respectively. The sensitivity of VMAT plans to MLC positional errors was similar to those of IMRT plans with less than 50 segments but much less than those created for a step and shoot with more than 50 segments or sliding-window delivery technique. To maintain the PTV70 to within 2% would require that MLC open/close errors be within 0.6 mm.
Fig. 2. Sensitivity of the EUDs of the structures of interest to systematic errors in all leaves. Every 1 mm error leads to average changes of 2.7% of the prostate CTV EUD and 5.6% of the H&N CTV EUD.

Fig. 8. Calculated results relating the error in the dose delivered to the error in the gap for a range of gap widths.
Tatsumi (2011) used 3 different TPS to create VMAT plans for 5 prostate cases and tested the pass rate when systematic MLC errors is introduced. The impact of leaf position errors on dose distributions depend upon the final optimization results. In agreement with the correlation between dose error and average leaf gap.
Conclusions

• An extensive and comprehensive commissioning program is necessary for VMAT and IMRT to understand the chain of the system

• To be aware about limits and capabilities of the system allows us to set parameters for a robust treatment plan

• To be aware about accuracy of the dosimetry system allows us to define a tolerance limits for dosimetric comparisons

• Linac delivery seems to be reliable

• TPS commissioning is the most important

• Patient specific QA cannot replace a comprehensive QA program