IMRT/VMAT: AAPM Recommendations for Commissioning and Delivery Verification

Emilie Soisson, Ph.D.
ICTP 2019
Learning Objectives

• To understand IMRT/VMAT commissioning and QA
• To be able to describe available measurement tools and analysis technique
• To be able to describe the limitations of each technique and future directions
Commissioning

• IMRT and VMAT can be available usually with minor hardware and software upgrades
• Validation can be challenging
• Commissioning is require for both planning and delivery to make sure planned doses can be delivered accurately
IMRT/VMAT – MLC tests

• Additional MLC tests may be required
  Dosimetry
  – Leaf gap
  – Transmission
  Mechanical
  – Speed
  – Positioning

MLC Characteristics


Inter- and Intra-leaf Leakage

PHYSICS CONTRIBUTION

COMMISSIONING AND QUALITY ASSURANCE OF RAPIDARC RADIOThERAPY DELIVERY SYSTEM

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Purpose: The Varian RapidArc is a system for intensity-modulated radiotherapy (IMRT) treatment planning and delivery. RapidArc incorporates capabilities such as variable dose-rate, variable gantry speed, and accurate and fast dynamic multileaf collimators (DMLC), to optimize dose conformity, delivery efficiency, accuracy and reliability. We developed RapidArc system commissioning and quality assurance (QA) procedures.

Methods and Materials: Tests have been designed that evaluate RapidArc performance in a stepwise manner. First, the accuracy of DMLC position during gantry rotation is examined. Second, the ability to vary and control the dose-rate and gantry speed is evaluated. Third, the combined use of variable DMLC speed and dose-rate is studied.

Results: Adapting the picket fence test for RapidArc, we compared the patterns obtained with stationary gantry and in RapidArc mode, and showed that the effect of gantry rotation on leaf accuracy was minimal ($\leq0.2$ mm). We then combine different dose-rates (111–600 MU/min), gantry speeds (5.5–4.3°/s), and gantry range ($\Delta \theta = 90^{\circ}–129^{\circ}$) to give the same dose to seven parts of a film. When normalized to a corresponding open field (to account for flatness and asymmetry), the dose of the seven portions show good agreement, with a mean deviation of 0.7%. In assessing DMLC speed (0.46, 0.92, 1.84, and 2.76 cm/s) during RapidArc, the analysis of designed radiation pattern indicates good agreement, with a mean deviation of 0.4%.

Conclusions: The results of these tests provide strong evidence that DMLC movement, variable dose-rates and gantry speeds can be precisely controlled during RapidArc. © 2008 Elsevier Inc.
Accuracy of MLC During RapidArc

Image of a film that was exposed twice to the 1-mm-wide picket fence pattern, once at stationary gantry angle and a second time in RapidArc mode.
A film exposed to the 1-mm-wide picket fence pattern with “intentional” errors in fence width and position.
Ability to vary Dose Rate and Gantry Speed

Film exposed to a RapidArc QA plan, combining different dose-rates, gantry ranges, and gantry speeds, to give the same monitor unit (MU) to the different parts of the field.
MLC Tests for VMAT

- **Test 0.1**: dMLC Dosimetry
- **Test 0.2**: Picket Fence Test vs. Gantry Angle
- **Test 1.1**: Picket Fence Test during RapidArc®
- **Test 1.2**: Picket Fence Test during RapidArc® with Intentional Errors
- **Test 2**: Accurate Control of Dose Rate and Gantry Speed during RapidArc® Delivery
- **Test 3**: Accurate Control of Leaf Speed during RapidArc® Delivery

RapidArc® is a registered trademark of Varian Medical Systems, Inc.

https://radimage.com/solutions/mlc-qa/
AAPM Medical Physics Practice Guideline 8.a.: Linear accelerator performance tests


D5 Dynamic delivery control

Volumetric modulated arc therapy (VMAT) and sliding window techniques are types of dynamic deliveries routinely used that require the synchronization of the dose rate with other dynamic components of the machine. To produce a dynamic delivery, some combination of multileaf collimator (MLC) position, MLC leaf speed, dose rate, and gantry speed and position are varied throughout the treatment. Patient-specific QA may not test the full range of these parameters, therefore, a monthly test of each of the dynamic control components used clinically is recommended. Tests have been designed to ensure the machine control of the individual dynamic components or to test them in combination by varying one dynamic control against another. Varian Medical Systems provides a series of tests for dynamic delivery along with the Digital Imaging and Communications in Medicine (DICOM) plans needed to execute them and spreadsheets to help with the analysis. In these tests, the gantry speed is varied against the dose rate control in one test and the MLC speed is varied against the dose rate control in another. Elekta provides similar tests at the time of acceptance. Or the user may design their own fields to test the different elements. With this
IMRT/VMAT Commissioning - TPS

- AAPM MPPG 5a recommends the following tests
- VMAT, Segmental IMRT, and Dynamic IMRT need to be validated separately

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
</tr>
</thead>
</table>
| 1     | Verify small field PDD  
<2x2cm², MLC shaped |
| 2     | Output for small MLC defined field                |
| 3     | AAPM TG-119 tests  
Plan, measure and compare benchmark cases |
| 4     | Clinical tests  
Plan, measure and compare representative clinical cases |
| 5     | External Review  
Sim, plan, and treat anthropomorphic phantom |

<table>
<thead>
<tr>
<th>Test</th>
<th>Objective</th>
<th>Description (example)</th>
<th>Detector</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>Verify small field PDD</td>
<td>≤ 2×2 cm² MLC shaped field, with PDD acquired at a clinically relevant SSD</td>
<td>Diode or plastic scintillator</td>
<td>Yunice et al.(^{(16)})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use small square and rectangular MLC-defined segments, measuring output at a clinically relevant depth for each(^ {a})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.2</td>
<td>Verify output for small MLC-defined fields</td>
<td>Plan, measure, and compare planning and QA results to the TG119 report for both the Head and Neck and C-shape cases</td>
<td>Diode, plastic scintillator, minichamber or microion chamber</td>
<td>Cadman et al.(^{(58)})</td>
</tr>
<tr>
<td>7.3</td>
<td>TG-119 tests</td>
<td>Choose at least 2 relevant clinical cases; plan, measure, and perform an in-depth analysis of the results</td>
<td>Ion chamber, film and/or array</td>
<td>TG-119 (Ezzell et al.(^{(37)}))</td>
</tr>
<tr>
<td>7.4</td>
<td>Clinical tests</td>
<td>Simulate, plan, and treat an anthropomorphic phantom with embedded dosimeters.</td>
<td>Ion chamber, film and/or array</td>
<td>Nelms et al.(^{(42)})</td>
</tr>
<tr>
<td>7.5</td>
<td>External review</td>
<td>Various options exist(^ {b})</td>
<td></td>
<td>Kry et al.(^{(39)})</td>
</tr>
</tbody>
</table>

\(^{a}\) A bar pattern scanned with a diode can be used to obtain additional absolute dose profile comparison in the direction perpendicular to MLC movement

\(^{b}\) If IROC Houston service is used, they typically employ TLDs and radiochromic film. Certain commercial phantoms can accommodate ion chambers for point dose measurements
MPPG 5A Additional Resources

PUBLICATIONS

MPPG-TPS

The Medical Physics Practice Guideline (MPPG) for Commissioning and QA of External Beam Treatment Planning System (TPS) Dose Calculations includes recommendations to validate the dose for IMRT/VMAT/helical delivery plans through comparison of the individual beams and/or composite measurements with TPS calculations. In addition, the MPPG recommends the establishment of a routine QA program that validates dose calculation consistency through recalculation of reference plans for photon and electron beams. The MPPG has provided six sample datasets (DICOM CT and RT Structure Sets) that are available for users to download.

IMRT/VMAT Validation Datasets

Plans should be developed using a dose calculation method that accounts for tissue heterogeneities in primary and scatter interactions (e.g., Convolution/Superposition, Monte Carlo, or grid-based Boltzmann transport equation solvers). The following datasets are available and include a PDF of sample objectives that can be used for optimization and prescription.

- Case 1: Prostate fossa and nodal region (Simultaneous Integrated Boost) [21MB]
- Case 2: Abdomen (Simultaneous Integrated Boost) [33MB]
- Case 3: Lung, Right upper lobe (single PTV) [47MB]
- Case 4: Anal (Simultaneous Integrated Boost) [22MB]
- Case 5: Head & Neck (Simultaneous Integrated Boost) [27MB]

Additional Routine QA Dataset

Dose calculation consistency can be performed by re-calculating a subset of the IMRT/VMAT datasets provided above and by using the following dataset for simple photon and electron fields.

- Case 6: Thorax for electron and/or photon beams (Chest Wall) [32MB]
Other IMRT/VMAT Commissioning

- ESTRO Booklet 9
- AAPM MPPG 5A
- AAPM TG119, 120, 218
- Read the manual!
AAPM Recommendations: Report of Task Group 120

Dosimetry tools and techniques for IMRT

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“This report provides a comprehensive overview of how dosimeters, phantoms, and dose distribution analysis techniques should be used to support the commissioning and quality assurance requirements of an IMRT Program.”
Phantoms
AAPM Recommendations: Point Dose

• Absolute dose
  – Calibrated cylindrical ion chamber
  – Size should be small enough to limit dose heterogeneity across the volume to <10%
  – Avoid high z central electrode
  – Leakage <5% of reading (correction >2%)

• Measurement location
  – Homogeneous (<10%)
  – <10% dose difference 2mm from detector

• Reference dose
  – Calculated average over collecting volume
  – Avoid point dose
AAPM Recommendations: 2D Detectors

• Detectors
  – Film
  – Diode Arrays
  – Ion chamber arrays
  – EPID

• Recommendations
  – Use for relative dosimetry
  – Film calibration protocol
  – Commissioning with film before moving to 2D arrays for routine QA
Diode Arrays
II.B.2.c. Recommendations for use

(1) Useful for efficient routine QA of a precommissioned IMRT technique. Initial commissioning should be performed with a system with higher spatial resolution (e.g., film).

(2) For calibration and all measurements with the device, the linear accelerator dose repetition rate should be the same as for the clinical treatment.

(3) The device calibration should be checked monthly, or as specified by the manufacturer or published literature.

(4) Careful consideration should be given to the development of pass/fail acceptance criteria for the evaluation of the results from an array detector. For example, AAPM Task Group 119 (Ref. 17) demonstrated pass rates of $>90\%$ of the evaluated points when using 3 mm/3% distance-to-agreement (DTA) and dose-difference criteria, respectively, when reporting institution's planar diode detector measurement QA results. Each physicist should determine acceptance criteria that are appropriate for the treatment site, the treatment objectives, and the clinic's policies.
V.A.2. Recommendations for use

Once an IMRT program has been started with ion chamber and film measurements, it may be appropriate to use an EPID for individual IMRT field verification measurements if a reliable method of operation has been developed. The EPID response must be characterized for a range of situations (e.g., dose, dose rate, field size, and leaf speed). Once the system is characterized, a number of corrections must be made to the system depending on the type of system and the composition of the detector. The presence of a fluorescent screen leads to an over-response of the detectors to low doses. To calculate a portal dose prediction or portal dose image for AMFPI systems, pencil beam,\textsuperscript{185} convolution,\textsuperscript{183} or Monte Carlo\textsuperscript{194} techniques have been used to approximate or model the interactions in the EPID including the effect of the fluorescent layer.

Some centers are utilizing commercial systems for IMRT dosimetry. When establishing a QA program with an EPID, the sensitivity of the system and the appropriate action levels and criteria for evaluation must be set.\textsuperscript{195} Further development of EPIDs for individual IMRT field verification and for patient transit dosimetry is expected to continue.\textsuperscript{191-193,196-200} Exciting developments include reconstruction of three-dimensional dose distributions.\textsuperscript{201}
Basic Pre-Treatment IMRT PSQA 
Rationale

• MU calculations and delivery are complex so a simple backup MU check may not be possible/adequate

• The patient’s plan can be measured by copying the plan to a phantom and performing a calculation of the patient’s fields on a phantom

• Point dose measurements in addition to a comparison of the planar dose distribution should be performed
Comparison of four commercial devices for RapidArc and sliding window IMRT QA

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Received 20052010: Accepted 13 December 2010

For intensity-modulated radiation therapy, evaluation of the measured dose against the treatment planning calculated dose is essential in the context of patient-specific quality assurance. The complexity of volumetric arc radiotherapy delivery attributed to its dynamic and synchronization nature require new methods and potentially new tools for the quality assurance of such techniques. In the present study, we evaluated and compared the dosimetric performance of EDR2 film and three other commercially available quality assurance devices: IBA I’MatriXX array, PTW Seven29 array and the Delta⁴ array. The evaluation of these dosimetric systems was performed for RapidArc and IMRT deliveries using a Varian NovalisTX linear accelerator. The plans were generated using the Varian Eclipse treatment planning system. Our results showed that all four QA techniques yield equivalent results. All patient QAs passed our institutional clinical criteria of gamma index based on a 3% dose difference and 3 mm distance to agreement. In addition, the Bland-Altman analysis was performed which showed that all the calculated gamma values of all three QA devices were within 5% from those of the film. The results showed that the four QA systems used in this patient-specific IMRT QA analysis are equivalent. We concluded that the dosimetric systems under investigation can be used interchangeably for routine patient specific QA.

PACS numbers: 87.55.Qr, 87.56.Fc

Key words: IMRT, quality assurance, photons, film dosimetry, RapidArc
How Often?

• Prior to delivery of every plan?
• When simple backup MU calculation is not possible or does not pass?
• Until you have data on X number of cases?
Canadian Partnership for Quality Radiotherapy

Technical Quality Control Guidelines for Patient-Specific Dosimetric Measurements for Intensity Modulated Radiation Therapies

A guidance document on behalf of:

Canadian Association of Radiation Oncology
Canadian Organization of Medical Physicists
Canadian Association of Medical Radiation Technologists
Canadian Partnership Against Cancer

July 4, 2016

PDM.2016.07.01

www.cpqr.ca
CPQR Recommendations

Test Tables

Table 1: IMRT quality control tests

<table>
<thead>
<tr>
<th>Designator</th>
<th>Test</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMRT1</td>
<td>Patient-specific IMRT quality control test</td>
<td>Complete</td>
</tr>
<tr>
<td>IMRT2</td>
<td>IMRT quality control test case</td>
<td>Complete</td>
</tr>
<tr>
<td>IMRT3</td>
<td>IMRT quality control constancy test</td>
<td>Complete</td>
</tr>
<tr>
<td>IMRT4</td>
<td>Patient-specific IMRT quality control procedure review of protocol</td>
<td>Complete</td>
</tr>
<tr>
<td>IMRT5</td>
<td>Independent audit or review</td>
<td>Complete</td>
</tr>
</tbody>
</table>

- IMRT1: PSQA
  - Or can be dropped with “rigorous” statistical analysis
- IMRT 2: Set of commissioning plans that mimic clinical cases
- IMRT 3: Case chosen for repeat delivery on quarterly basis
- IMRT 4: Annual review of IMRT protocol (passing criteria, methods, frequency, etc.)
- IMRT 5: External audit
IROC Audit
Credentialing results from IMRT irradiations of an anthropomorphic head and neck phantom

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(Received 10 April 2012; revised 15 November 2012; accepted for publication 7 December 2012; published 8 January 2013)

Results: The phantom was irradiated 1139 times by 763 institutions from 2001 through 2011. 929 (81.6%) of the irradiations passed the criteria. 156 (13.7%) irradiations failed only the TLD criteria, 21 (1.8%) failed only the film criteria, and 33 (2.9%) failed both sets of criteria. Only 69% of the irradiations passed a narrowed TLD criterion of ±5%. Varian-Elipse and TomoTherapy-HiArt combinations had the highest pass rates, ranging from 90% to 93%. Varian-Pinnacle³, Varian-XiO, Siemens-Pinnacle³, and Elekta-Pinnacle³ combinations had pass rates that ranged from 66% to 81%.

Criteria +/− 7%DD, 4mm DTA
Reasons for Failing Results

• Incorrect data entered into the TPS
• Inexact beam modeling
• Software and hardware failures
AAPM TG 119: Commissioning Tests for IMRT

• Reaction to RPC results showing failing IMRT QA results at many institutions
• Created a set of standard plans and analysis techniques to commission IMRT
• Compared results between institutions
IMRT commissioning: Multiple institution planning and dosimetry comparisons, a report from AAPM Task Group 119
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TG 119 Continued

• Treatment plans were created and analyzed in several institutions
• Recommendations for action and tolerance provided
• Data sets are available for download on the AAPM web site to allow individual sites
  – Allow for comparison to these sites using the same data sets
• Suggested that these standard plans be used in commissioning to improve results
• Provide baseline tests for machine changes
PUBLICATIONS

Test Suite by Task Group 119

The material was prepared by TG119 to assist with IMRT commissioning process. It is a test suite of mock clinical cases for IMRT planning and QA measurements.

AAPM grants permission to equipment manufacturers to use the dataset, with the use of the following disclaimer:

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- The instructions for planning, measurement, and analysis are included in the following PDF.
- Download the excel data report form.
- The CT and structure package in DICOM format is in this zip file.
- IMRT commissioning: Multiple institution planning and dosimetry comparisons, a report from AAPM Task Group 119
Gamma Passing Rate

• Percentage of points analyzed that pass the DD and DTA criteria
• General looking for pass rates above 90%
• Wide variety in practice in the USA/Canada
Gamma Index

Gamma is the Euclidian distance between an evaluated distribution and each point in an evaluated distribution. Gamma is a tool to compare dose distributions. It has limitations that must be considered in IMRT QA analysis.

\begin{equation}
\Gamma(\vec{r}_e, \vec{r}_r) = \sqrt{\frac{[\vec{r}_e - \vec{r}_r]^2}{\Delta d^2} + \frac{[D_e(\vec{r}_e) - D_r(\vec{r}_r)]^2}{\Delta D^2}}
\end{equation}

where \( \vec{r}_e \) and \( \vec{r}_r \) are the vector positions of the evaluated and reference points, respectively, \( D_e(\vec{r}_e) \) and \( D_r(\vec{r}_r) \) are the evaluated and reference doses, respectively, and \( \Delta d \) and \( \Delta D \) are the DTA and dose difference criteria, respectively. The generalized \( \Gamma \) function can be computed for any pair \( \vec{r}_e \) and \( \vec{r}_r \), so for each reference point, there are as many values of \( \Gamma \) as there are evaluated points (infinite number with interpolation). The minimum value of \( \Gamma \) is the value of \( \gamma \).

\begin{equation}
\gamma(\vec{r}_r) = \min \{ \Gamma(\vec{r}_e, \vec{r}_r) \} \forall \vec{r}_e
\end{equation}

Equation 2 states that \( \gamma \) is simply the minimum value in all of the evaluated distribution search space of \( \Gamma \). While equations 1 and 2 provide the factual definition of \( \Gamma \), they do not impart any intuition for what \( \gamma \) means and its utility.

Dosimetry tools and techniques for IMRT
Pitfalls of the Gamma Index

Evaluating IMRT and VMAT dose accuracy: Practical examples of failure to detect systematic errors when applying a commonly used metric and action levels

Benjamin E. Nelms, Maria F. Chan, Geneviève Jarry, Matthieu Lemire, John Lowden, Carnell Hampton, and Vladimir Feygelman

Citation: Medical Physics 40, 111722 (2013); doi: 10.1118/1.4826166
View online: http://dx.doi.org/10.1118/1.4826166
View Table of Contents: http://scitation.aip.org/content/aapm/journal/medphys/40/11?ver=pdfcov
Published by the American Association of Physicists in Medicine
Conclusions Nelms et al.

• Real-world cases where systematic errors were not detected with 3%/3mm
  – Error introduced to TPS, linac, delivery method, setup

• More sensitive metrics should be used to evaluate the accuracy of dose calculation algorithms, delivery systems, and QA devices.
Gamma analysis dependence on specified low-dose thresholds for VMAT QA

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Gamma analysis dependence on specified low-dose thresholds for VMAT QA
Gamma analysis dependence on specified low-dose thresholds for VMAT QA

Local normalization
Conclusion

• The low dose threshold that is chosen and the normalization technique, global or local, greatly impact Gamma passing rates
Impact of Noise on Gamma Analysis

Figure 1 (a). Graphical interpretation of the $\gamma$-index in one-dimension. (b). An example demonstrating how the $\gamma$-index value changes due to MC statistical fluctuations in the evaluation dose. (c). An example demonstrating how the $\gamma$-index value changes due to MC statistical fluctuations in the reference dose.

Conclusion

• Gamma can be artificially high or low depending on the noise in either your measured or calculated distribution
Recommendations for Gamma

- Need interpolation between calc points to get good results
- Noisy distributions result in artificially low gamma results
- Don’t blindly use pass/fail criteria
- If points fail by a lot, look at this point
- Know where anatomically the points fail
Tolerance limits and methodologies for IMRT measurement-based verification

QA: Recommendations of AAPM Task Group No. 218

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Recommendations from AAPM TG 218 (in press)

- Measurements should be a true composite
  - Ensure detector has no angular dependence
  - No perpendicular composite, prone to masking delivery errors
- Absolute Dose vs. Relative dose
- Exclude areas with little or no clinical relevance
  - Ignore large areas of low dose that change the pass rate
- Calibration compared against a standard dose at each measurement
- Normalization
  - Global versus local normalization
  - Normalization point should be in a low gradient, high dose region \( \geq 90\% \) of the max dose
  - Local normalization can be used for commissioning
218 Recommendations Cont.

- **Tolerance and action**
  - Tolerance ≥95% with 3%/2mm
  - Action ≥90% with 3%/2mm
  - Ignore points <10% of rx dose

- **Resolution is important for gamma analysis, need to use DTA of <3mm to detect MLC errors**
  - Understand software

- **Site specific tolerance and action levels are encouraged as long as it is better than these universal recommendations**
  - For example if at your site you can only get 80%/3mm, then you have to do better.

- **Make sure you have the appropriate equipment**

- **Log results to know how you are doing**
What to do when plans fail

• Look at where it fails and determine if it is relevant
• Don’t just look at statistics, look at all points above gamma 1.5
• Replanning should be an option (allow ample time for QA)

• Failing Gamma rates should be investigated!
Clinical Example
Head and Neck PSQA w/ArcCheck
Beam Enters through Couch
Beam that Does Not Enter Through Couch
Composite
Other IMRT Verification Methods

- Software that analyses beam delivery files (i.e. Varian Dynalogs, Mobius)
- Import plan DVH and compare to library of standard plans or set of established dose constraints to assess plan quality
- Second TPS or Monte Carlo
Use of Treatment Log Files (3D)

- Record treatment leaf position
- 3D delivered dose is calculated in the patient CT using collapsed cone convolution
- Allows for assessment of the impact of delivery errors on dose to the patient
Role of Mobius in Automating QA

SafetyNet: streamlining and automating QA in radiotherapy
Other IMRT Verification Methods

• In general, these methods do not look at accuracy of heterogeneity corrections
• Calculate plan in a second treatment planning system
LifeLine Software acquires Radify Monte Carlo QA Technology from McGill University

AUSTIN, TEXAS, 24 July 2017 – LifeLine Software, Inc., a worldwide leader in dosimetric quality assurance tools, is pleased to announce that an agreement has been signed to acquire Radify, a Monte Carlo 3D dose volume QA software technology developed at McGill University in Quebec, Canada.

This acquisition and joint collaboration allows LifeLine Software to bring to market industry-changing 3D dose volume independent dosimetric verification products. LifeLine Software’s integration of the Radify technology will immediately improve accessibility to the significant advantage of Monte Carlo accuracy in clinical settings, specifically for verifying photon, electron, and proton treatment plans.

Monte Carlo is widely recognized as the gold standard dose calculation method. The most challenging clinical cases and complex structures are analyzed with the highest accuracy and confidence. Flexible implementation options and the uncompromised accuracy of a Monte Carlo dose calculation algorithm assist radiation departments to meet their workflow requirements.
Radify Interface

Proportion of complex plans increasing resulting in a need for more accurate MU verification. Improved accuracy may eliminate the need for measurements.

Slide courtesy of Marc-André Renaud
Dose Difference

Figure 4: Dose difference: Eclipse AAA with heterogeneity corrections vs MC

Slide courtesy of Marc-André Renaud