Whitepaper: Implementation of Mobius3D by Hull University Teaching Hospitals

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An introduction by Varian, a Siemens Healthineers Company

Varian has been in the Quality Assurance (QA) space for a long time, starting with products such as Argus and Portal Dosimetry. In 2018 Varian established a dedicated QA portfolio, focusing exclusively on machine and patient QA. With the acquisition of DoseLab, Mobius3D, and Qumulate, we have been expanding and strengthening our portfolio to provide a comprehensive QA solution for all steps of a patient's treatment journey.

Why did Varian join the QA space?

As Varian, we are dedicated to providing QA solutions that provide our users with the tools and results to ensure safe high-quality patient treatments. Our goal is to release patient QA with new modalities and enable emerging technologies such as online adaptive radiotherapy. With the rapidly increasing complexity and number of treatments QA has become a significant part of the patient's treatment process. We therefore believe that QA workflows should be automated and standardized. Due to our close collaboration with the other product teams, we can create these integrated and automated solutions.

Our vision (February 2022)

For Mobius3D, our vision is to deliver automated QA for every plan and every treatment, to ensure that patients are treated with the correct plan and with the correct dose. We listen to the market needs, implement established guidelines, and collaborate closely with our other products to build the features that give our users confidence in their QA and treatment workflow. We do this by taking the following design goals into consideration:

- A feature shall improve the user's workflow and QA experience. Where possible, it will increase the efficiency and lead to time-savings (less machine and physicist time). This is realized by automating where possible and through integration with other products;
- A feature shall provide results that are reliable and actionable. Large numbers of false positives are not acceptable, as they create documentation indicating patient mistreatment with no ability to correct their root cause. Furthermore, they add significant additional work to determine if the patient's treatment is safe. Large numbers of false negatives are clearly unacceptable, because they miss what may be a real problem with patient safety. The goal is to design solutions that identify the root cause of an error.

While patient QA has been maturing over recent decades, continuous improvements are necessary to keep up with the ever-changing field of radiotherapy. With this in mind, our short-term focus is on improving the existing product, and adding new features such as those that ensure better integration and also provide ultimate patient safety such as EPID (Electronic Portal Imaging Device) based QA. In the long-term we expect QA to become more tightly integrated in the entire treatment chain, performing automated QA on each process carried out.

What is Mobius3D?

Mobius3D (M3D) is a patient QA system that allows your existing hardware to be transformed into a complete patient delivery verification tool. The four main modules are:

- MobiusCalc: Secondary dose calculation of the TPS (Treatment Planning Systems) plan using our independent beam model and dose algorithm. Verifies that the dose to the targets and organs at risk are within the user-defined limits;
- MobiusFX: (Pre-)Treatment QA using machine measurements. On top of the results provided by MobiusCalc, MobiusFX also verifies that the scheduled plan is delivered, and the machine delivered it within the user-defined limits;
- MobiusCB: Checks the CBCT (Cone Beam Computed Tomography) against the planning CT (Computed Tomography) with a density gamma comparison to highlight gross errors in patient positioning and significant changes in patient anatomy. Calculates and visualizes dose on the CBCT to understand the impact of any patient anatomy or alignment changes to the dose distribution;
- MobiusAdapt: Secondary dose QA for online adaptive plans created by Ethos™ therapy.

Mobius3D uses independent customizable beam models for a wide range of machines and modalities. The independent CCCS (collapsed cone convolution superposition) dose algorithm is developed by Varian. The software comes pre-installed on a Varian provided and installed server. The application is browser based. After configuration almost the entire workflow is automated, reducing the time spent on QA.

Is Mobius3D independent and how is this guaranteed?

To guarantee independence, Mobius3D aligns with clinical guidance in that we:

- Have individual engineering teams and Product Managers who focus exclusively on QA products;
- Collaborate closely with other products to optimize workflows and designs without re-using their code and methodologies;
- Aim to follow standardized protocols such as DICOM (Digital Imaging and Communications in Medicine) or use data accessible to the user;
- Created independent beam models and dose algorithm.

Why this whitepaper?

As Varian we provide various resources around Mobius3D and its commissioning. This white paper contains recommendations for the commissioning process, suggested tolerances, and expected differences. Our intention is to give our (potential) users the opportunity to understand how this might work out in practice. Hull University Teaching Hospitals has been using Mobius3D for several years and spent significant effort on the implementation within their clinic. Understanding their goals and processes as an independent user will help our existing and new users with their implementation of Mobius3D.

Abstract

This work gives an overview of the commissioning of Mobius3D for clinical use for both Halcyon and C-Arm linacs for VMAT (Volumetric Modulated Arc Therapy), Conformal RT (Radiation Therapy) and Virtual Simulation techniques. Comparisons of Mobius3D calculations and physical measurements agree within ±3%. Mobius3D calculations compared to TPS calculated dose for both AAA and AXB, meet at least the 5%/3mm gamma pass rate of 90% for all complex plans.

Local clinical workflow is described, which stratifies plans with three action levels to allow appropriate identification of plans requiring further investigation. The workflow also includes use of an ESAPI script, which allows the user to interrogate the Mobius3D database and produce a custom QA report without leaving the ARIA environment. Time saving efficiencies of eight minutes per plan check have been achieved for over 90% of calculations.

An Introduction to Hull University Teaching Hospitals

Hull University Teaching Hospitals is a large acute National Health Service (NHS) provider located in England. The Trust provides a wide range of NHS services which includes cancer care. The department comprises six Varian Linear accelerators providing external beam radiotherapy and also has superficial and brachytherapy services. The Radiotherapy Physics service excels in its commitment to the scientific support and development of services, evidenced by the United Kingdom Accreditation Service recognizing the service meets the requirements of the BS70000 Medical Physics and Clinical Engineering Quality Standard. This accreditation provides assurance of a technically competent and high-quality scientific service to the department's patients, who receive approximately 41,000 fractions of radiotherapy per annum. The Radiotherapy department is part of the Yorkshire and Humber Operational Delivery Network for Radiotherapy.

The Radiotherapy department has a long history of implementing new and emerging technology into the clinical pathway and was amongst the first few departments to offer IMRT in England, in 2002. As with other early adopters, the department was initially limited in its ability to deliver IMRT to all clinical sites owing to inefficiencies and lack of advanced technology for treatment verification and validation. However, there was a strong commitment to achieve access to IMRT for all patients that would benefit. As new technology became available and clinical pathways were streamlined, the number of IMRT

episodes delivered increased significantly, as shown in **Figure *1***.

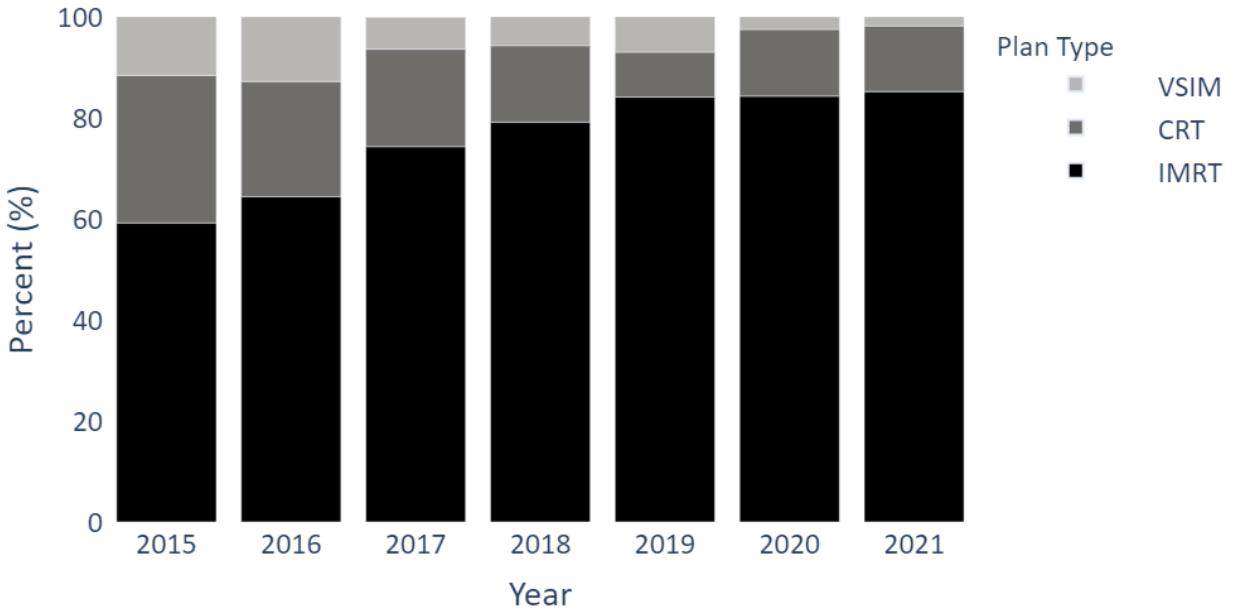

Figure 1 Relative number of plans produced by treatment planning per year, broken by type into Virtual Simulation (VSIM), Conformal Radiotherapy (CRT) and Intensity Modulated Radiotherapy (IMRT). For a sense of absolute scale, the median total number of plans produced over this period is approximately 2300 per year. Note, this graph excludes VSIM plans produced on a separate, radiographer-led pathway.

The drive to improve access to modernised treatments has continued with the department being the first in the North of England to install and clinically commission a Varian Halcyon linear accelerator. The Halcyon has increased the flexibility of the overall service.

The physics team also has a well-established precedence of implementing efficiencies into the clinical workflow. Previous local work has shown that patient specific quality assurance (PSQA) dosimetric measurements are not required for individual patient plans, provided there is traceability between computer simulation tolerances and measurement-based QA methodologies. By reducing the requirement for machine-based physical measurements, there has been an associated reduction in the resource requirements of both (staff and equipment). This has consequently increased clinical pathway throughput.

The implementation of the Halcyon in the department also provided a new challenge: a requirement for an independent verification system to provide quality assurance for clinical treatment plans. In summary, a solution was required that would:

1. allow independent treatment plan verification by quantitative analysis for external beam clinical radiotherapy treatment plans;
2. enable traceability between independent dose calculation results and physical measurements;
3. support automation and reduced requirement for user input in the clinical workflow;
4. support both Varian Halcyon and Varian TrueBeam Linac models, to enable standardized operating procedures for Quality Assurance procedures within the departmental fleet, irrespective of the delivery device;
5. Facilitate future development of the clinical service to monitor treatment delivery after each fraction and provide assurance that the treatment unit had performed within the required tolerances.

Reviewing the options available, the MobiusCalc and MobiusFX modules provided the required functionality to achieve all these objectives. This whitepaper described the commissioning and implementation of the MobiusCalc module, referred to generically as Mobius3D (M3D) throughout.

Clinical Implementation

The initial implementation for M3D was driven by various demands and may not necessarily be seen as the most natural order in which to implement the software. The entire rollout was done in three main phases.

Phase 1: Halcyon VMAT

At the time of the initial installation of a Halcyon in March 2019, no commercial solutions existed for the independent QA of plans on this machine. As such, all plans had point dose measurements performed with ionisation chambers. This required considerable amounts of both machine and physicist time. Due to this demand on resources the first implementation of M3D was for our cohort of Halcyon patients (Pelvis VMAT at that time).

Phase 2: C-Arm Breast and Conformal RT

Following on from this M3D was rolled out to breast plans (sliding window IMRT with CRT boosts), and other CRT plans. This cohort used point-dose independent MU (Monitor Units) calculation software, which was end-of-life and as such needed to be replaced.

Phase 3: C-Arm Linac VMAT

The final phase of the rollout was to the remainder of the clinical portfolio, which in our clinic was VMAT to all sites on standard C-arm linacs.

Commissioning

Materials and Methods

The M3D documentation provided some suggestions of expected accuracy for both the commissioning process and volumetric calculations. These were related to the accuracy of M3D rather than clinical acceptability, which remains the responsibility of the local Centre. In addition to comparing against the suggested performance, we also utilized several tests that form part of linac or TPS commissioning. It should be noted that local experience of M3D is currently limited to 6MV and 15MV flattened beams on a TrueBeam and 6MV-FFF on a Halcyon.

Open field beam model

The first stage of commissioning the beam model was to assess the basic model for simple open fields on a water phantom. There were two aspects to this assessment. Firstly, comparison of beam model parameters to point dose measurements, and secondly, volumetric gamma comparisons between M3D and TPS calculations.

Point dose measurements

M3D has a Beam Model Customization page, which contains several beam parameters. These parameters may be modified to fit the local data if required. They can also be compared to point dose measurements for verification purposes. For the commissioned machines these include:

- PDD (Percentage Depth Dose) values at 5cm, 15cm and 25cm depths for 5cm x 5cm, 10cm x 10cm and 20cm x 20cm field sizes (not available for Halcyon models);
- Off-axis Ratios up to 20cm, at 5cm depth for a 40cm x 40cm field at 100cm SSD (Source to Surface Distance) (not available for Halcyon models);

- Output Factors from 3cm x 3cm to 40cm x 40cm at 10cm depth and 100cm SSD.

These values were compared to measurements acquired during the commissioning of local treatment units. If deviations exist, the values can be modified to improve the agreement. Measurements were performed with a CC13 ionization chamber in the Blue Phantom 2 (IBA Dosimetry) plotting tank. 1cm x 1cm and 2cm x 2cm output factors were included in the Mobius commissioning data. However, as the local field size limit is 3cm x 3cm and small MLC (Multi Leaf Collimator) segments would be more significantly influenced by the MLC parameters, these were not considered here. Output factors for cone applicators were also included the M3D commissioning data. However, these are not in use locally and were not considered in this work.

Gamma Comparisons

A series of open fields from 5cm x 5cm to 40cm x 40cm were applied to a water phantom (60cm x 60cm x 60cm), large enough for full scatter conditions. 3D gamma comparisons were made (3%/3mm and 2%/2mm) with TPS dose distributions, with an expected pass rate of at least 90% for 3%/3mm as per recommendation in M3D Instructions for Use. The regions of expected deviations are in the penumbra, build-up region and off-axis positions for large fields.

Inhomogeneity Phantom Measurements

The accuracy of the system for inhomogeneities and more complex open fields were performed based on IAEA-TECDOC-1583 (TecDoc, 2008). The phantom used was IMRT Thorax Phantom (CIRS) and measurements were acquired with the CC13 Ionization chamber and Dose 1 electrometer (IBA Dosimetry). Eight cases were assessed for each energy on the C-arm linacs. This was repeated for Halcyon, with the two cases for assessing wedges not included. The measurements are performed as part of the treatment unit commissioning and the M3D calculations were compared to an average set for the three local TrueBeams or the single set for the Halcyon.

- Case 1: Basic 10x10cm^2 anterior field, measurements in ‘water’;
- Case 2: Tangential field with wedge, scatter-loss and surface obliquity, measurements in ‘water’;
- Case 3: Direct anterior field with MLC ‘diamond’ shaped field, measurements in ‘water’;
- Case 4: Four field brick, lateral transmission through ‘lung’, posterior transmission through ‘bone’, measurements in ‘water’, ‘lung’ and ‘bone’;
- Case 5: Anterior field, through ‘lung’ and ‘water’ sections, measurements in ‘water’ and ‘lung’;

- Case 6: Oblique incident field with significant MLC blocking, measurements in ‘water’, ‘lung’ and ‘bone’;
- Case 7: Three field, with lateral wedges, lateral transmission through ‘lung’, measurements in ‘water’;
- Case 8: Non-coplanar fields, anterior-inferior oblique field, lateral fields with transmission through ‘lung’, measurements in ‘water’.

Mobius Verification Phantom

The Mobius Verification Phantom (MVP) was used for commissioning, which is constructed from water equivalent material and has seven positions for point dose measurements and space for film in the coronal plane. M3D has an in-built feature that may calculate an imported plan on the MVP. This removes the requirement to recalculate clinical plans on the phantom if performing verification measurements. However, it does not consider the couch and assumes the phantom is positioned at the external markers. To assess the suitability of this feature, a range of plans were applied to a locally acquired CT scan of the MVP in Eclipse and exported to M3D. The calculations in M3D on the CT scan were compared to the in-built calculations.

Figure 2: Mobius Verification Phantom with seven measurement points and a slice for holding film. Manufactured from water equivalent material.

Optimization of Dosimetric Leaf Gap Correction

Once the base beam model has been verified, complex IMRT plans can be reviewed. The initial step is the optimization of the Dosimetric Leaf Gap (DLG). The DLG has been configured as part of the provided model. Adjustments can be made using the parameter "DLG correction from M3D's default", which defaults to 0.0mm. This is the only adjustable value in M3D for modelling the MLC and can significantly impact on the small field segments used in IMRT. The method for this optimization is to acquire a series of point dose measurements for a representative range of patients. Then the DLG correction is adjusted to minimize the difference between M3D calculations and these measurements. At this point the DLG correction can be used to compromise for inaccuracies in the base beam model, which is why it is important to verify simple cases first. There is also a possibility of over fitting the DLG correction to the sample of patients used, and that it will not be suitable for others. The patient sample should cover the range of patient sites and treated volume sizes to optimize to all types of fields generated.

Once the DLG correction was optimized, a second independent set of point dose measurements for an independent patient sample was used to validate the model. This step helped to ensure that the model was not over-fitted for an unrepresentative patient group or that there was an issue with the initial point dose measurements.

Clinical Plan Point Dose Measurements

The locally installed Halcyon was v2.0 and used both sets of MLCs for modulation. As this was not modelled in M3D prior to v3.0, a large sample of dose measurements (186 plans) were acquired using the MVP for verification purposes. The phantom was CT scanned with, and without, a CC13 ionisation chamber (IBA Dosimetry) inserted. The active volume of the chamber was contoured and copied to each measurement position to allow an average dose to each position to be calculated. For each plan, the measurement points were assessed in Eclipse and a suitable one was identified; a point with a standard deviation <1% of the mean dose. If none of the points met this criteria, isocentre moves were applied until a suitable point is found. The measurements were performed with a Dose 1 electrometer and CC13 ionisation chamber (IBA Dosimetry). The measurements were normalised to the reference output and have an uncertainty of ±0.5% (95% CL: k =2). IPEM Report 96 (James et al., 2008) suggests a point dose tolerance of 2-5% depending on the complexity.

For the in-built MVP calculation, the dose at each of the seven ion chamber locations and the standard deviation is shown. Each measurement point ROI (Regions of Interest) is ~0.5 cm^3. The measurement point ROIs are much larger than the supported ion chambers (~0.13 cm^3) to account for up to a 3 mm

setup error. Once M3D v3.0 was available a sample of previous point dose measurements were compared to the M3D in-built feature and an exported plan on the MVP CT series. The differences between the methods were compared to determine if the limitations of the in-built feature are significant or not.

Plan Comparisons

A range of plans were recalculated in M3D and compared to the TPS dose distributions. The M3D documentation states that the following performance should be expected:

- Simple Plans: gamma pass rates with 5%/3mm criteria should be above 98% and mean target difference should be within ±3%;
- Complex Plans: gamma pass rates with 5%/3mm criteria should be above 90% and the target mean dose difference should be within ±5%.

Deviations should be limited to regions of inhomogeneity or near the surface of the patients, and so this was investigated. The 'Target' for these comparisons is a structure that combines all PTV (Planning Target Volume) volumes for that treatment, known as the combined target volume. The volume within the patient CT used for the gamma comparison is the region within the 10% dose threshold of the maximum dose. These comparisons were used to determine suitable tolerances based on the observed performance for the local plans and TPS.

Results

Simple Point dose measurements

Halcyon

For the output factor comparisons, it is suggested in the M3D documentation that agreement should be within ±3.0%, within a further constraint of ±0.5% if improved accuracy is required. All M3D comparisons (**Table *1***) met the tighter constraint for both TPS calculation and measurement comparisons, except for the 2cm x 2cm comparison to the TPS. Since the M3D calculation were within the tighter constraint for the measurements, and small MLC field calculations will be further assessed during the validation of complex IMRT deliveries, this was considered acceptable.

Table 1: Output Factor comparisons for Halcyon 6MV-FFF fields; deviations between M3D and TPS or Measurement (negative deviations indicate underestimation of the dose in M3D).

Field Size (cm x cm)	Deviation from TPS	Deviation from Measurement
2	**0.7%**	-0.1%
4	-0.1%	-0.2%
6	-0.1%	-0.1%
8	-0.1%	0.0%
10	-0.2%	0.0%
14	-0.2%	0.1%
20	-0.2%	0.0%
24	0.0%	-0.1%
28	-0.2%	-0.2%

TrueBeam

For the output factor comparisons, it is suggested in the M3D documentation that agreement should be within ±3.0%, within a further constraint of ±0.5% if improved accuracy is required. 6MV (**Table *2***) and 15MV (**Table *3***) M3D calculations met the tighter constraint, other than the 3cm x 3cm 15MV comparison to measurement, which only met the ±3% constraint.

Table 2: Output Factor comparisons for TrueBeam 6MV fields; deviations between M3D and TPS or Measurement (negative deviations indicate underestimation of the dose in M3D).

Field Size (cm x cm)	Deviation from TPS	Deviation from Measurement
3	0.0%	-0.1%
5	0.3%	0.2%
10	0.0%	0.0%
15	0.2%	0.1%
20	-0.1%	0.2%
30	-0.2%	0.0%
40	-0.1%	-0.1%

Table 3: Output Factor comparisons for TrueBeam 15MV fields; deviations between M3D and TPS or Measurement (negative deviations indicate underestimation of the dose in M3D).

Field Size (cm x cm)	Deviation from TPS	Deviation from Measurement
3	0.1%	-1.8%
5	-0.3%	-0.2%
10	0.0%	0.0%
15	-0.1%	-0.1%
20	-0.2%	-0.1%
30	-0.1%	-0.2%
40	-0.2%	-0.4%

For the PDD comparisons, it is suggested in the M3D documentation that agreement should be within ±3.0%, within a further constraint of ±1.5% if improved accuracy is required. 6MV (**Table *4***) and 15MV (**Table *5***) M3D calculations met the tighter constraints for both TPS and measurement comparisons.

Table 4: PDD comparisons for TrueBeam 6MV; deviations between M3D and TPS or Measurement (negative deviations indicate underestimation of the dose in M3D)

Field Size (cm x cm)	5cm Depth		15cm Depth		25cm Depth	
	TPS	Meas.	TPS	Meas.	TPS	Meas.
5 x 5	-1.0%	N/A	-0.8%	N/A	-0.5%	N/A
10 x 10	-0.8%	-0.1%	-0.8%	0.1%	-1.3%	-0.6%
20 x 20	-0.5%	0.1%	-0.6%	0.1%	-0.4%	0.0%

Table 5: PDD comparisons for TrueBeam 15MV; deviations between M3D and TPS or Measurement (negative deviations indicate underestimation of the dose in M3D)

Field Size (cm x cm)	5cm Depth		15cm Depth		25cm Depth	
	TPS	Meas.	TPS	Meas.	TPS	Meas.
5 x 5	-0.8%	N/A	-0.7%	N/A	-0.6%	N/A
10 x 10	-1.0%	0.2%	-1.0%	0.0%	-0.7%	0.1%
20 x 20	-0.7%	0.1%	-0.5%	0.4%	0.0%	0.4%

For the off-axis comparisons, it is suggested in the M3D documentation that the agreement should be within ±3.0%, with a further constraint of ±2.0% if improved accuracy is required. 6MV (Table 6) and 15MV (Table 7) M3D calculations met the tighter constraints for both TPS and measurement comparisons.

Table 6: Off-Axis comparisons for a TrueBeam 40cm x 40cm 6MV field; deviations between M3D and TPS or Measurement (negative deviations indicate underestimation of the dose in M3D)

Off Axis Distance (cm)	Deviation from TPS	Deviation from Measurement
0.0	0.0%	0.0%
1.0	0.0%	0.2%
2.5	0.0%	-0.1%
5.0	0.6%	0.4%
7.5	0.2%	0.5%
10.0	0.4%	1.0%
15.0	0.9%	1.4%
20.0	1.3%	1.2%

Table 7: Off-Axis comparisons for a TrueBeam 40cm x 40cm 15MV field; deviations between M3D and TPS or Measurement (negative deviations indicate underestimation of the dose in M3D)

Off Axis Distance (cm)	Deviation from TPS	Deviation from Measurement
0.0	0.0%	0.0%
1.0	-0.1%	0.2%
2.5	0.1%	-0.1%
5.0	0.1%	-0.1%
7.5	-0.3%	0.0%
10.0	-0.5%	0.0%
15.0	-0.3%	0.2%
20.0	0.8%	-0.4%

Simple Plan Water Phantom Gamma Comparisons

Table *8* shows the gamma pass rates for 3%/3mm and 2%/2mm for 6MV-FFF on a Halcyon and 6MV and 15MV on a TrueBeam. Only the 40cm x 40cm field for 6MV on the TrueBeam does not meet the 90% 3%/3mm suggestion. Reviewing the distribution, the deviations are just over the 3% limit and only occur at depths greater than 25cm. The majority of the clinically relevant situations also meet 90% pass rate for 2%/2mm. There is a worsening agreement with 40cm x 40cm for both energies, however most of the differences are between 20cm and 50cm depth. Adjusting the parameters to improve the fit in these regions would impair the performance in more superficial regions and/or smaller field sizes. Since the lower performance is in situations that are unlikely to occur clinically in the local centre, the parameters were not adjusted.

Table 8 Gamma pass rates in a water phantom for both Halcyon [H] and TrueBeam [TB]. The maximum field size for the Halcyon is 28cm x 28cm and no fields larger than this were measured for this linac. The 28cm x 28cm field size was not measured for the TrueBeams. These are indicated by N/A in the Table. Values exceeding the 90% pass rate are shown in bold. 40cm x 40cm field disagreements are generally at depths >25cm, up to 50cm.

Field Size (cm x cm)	[H] 6MV-FFF 3%/3mm	[TB] 6MV 3%/3mm	[TB] 15MV 3%/3mm	[H] 6MV-FFF 2%/2mm	[TB] 6MV 2%/2mm	[H] 15MV 2%/2mm
5 x 5	100.0%	100.0%	100.0%	88.6%	92.6%	89.9%
10 x 10	99.8%	100.0%	99.6%	88.3%	98.2%	96.3%
15 x 15	100.0%	100.0%	99.4%	95.6%	97.7%	95.1%
20 x 20	99.7%	99.9%	99.0%	92.1%	96.9%	94.7%
28 x 28	97.6%	N/A	N/A	91.6%	N/A	N/A
30 x 30	N/A	99.9%	99.2%	N/A	**77.2%**	94.9%
40 x 40	N/A	**80.1%**	91.8%	N/A	**30.5%**	**70.2%**

Inhomogeneity IMRT Thorax Phantom Measurements

The deviations from M3D calculations to both point dose measurements and TPS calculations using Anisotropic Analytical Algorithm (AAA) (Varian Medical Systems) algorithm are shown for 6MV-FFF on a Halcyon (**Table *9***), and 6MV (**Table *10***) and 15MV on a TrueBeam (**Table *11***). For Halcyon cases, there is a systematic increase of dose in M3D for 'water' positions, with more variable comparisons in 'lung' and

'bone'. M3D performs better than AAA for Case 2 with the tangential oblique field, which is expected due to the differences in scatter modelling between the algorithms for oblique surfaces.

Table 9 Comparisons between M3D calculations and both point dose measurements and TPS calculations using AAA for Halcyon 6MV-FFF for the IAEA-TECDOC-1583 cases. Cases 7 and 8 contain wedges and consequently were not measured on the Halcyon.

Case	Position	[H] 6MV-FFF Measured	[H] 6MV-FFF AAA
1	Water1	3.1%	3.2%
1	Water3	2.6%	2.3%
1	Water5	1.9%	1.8%
1	Lung9	-2.2%	-1.1%
1	Bone10	-1.5%	-1.1%
2	Water1	-1.4%	3.2%
3	Water3	2.7%	2.5%
4	Water5	1.7%	2.8%
4	Lung6	1.0%	0.9%
4	Bone10	-2.2%	-2.3%
5	Water2	2.5%	2.2%
5	Lung7	0.7%	-0.5%
6	Water3	3.0%	3.7%
6	Lung7	4.7%	1.9%
6	Bone10	0.5%	0.2%

Table 10 Comparisons between M3D calculations and both point dose measurements and TPS calculations using AAA for TrueBeam 6MV for the IAEA-TECDOC-1583 cases.

Case	Position	[TB] 6MV Measured	[TB] 6MV AAA
1	Water1	1.0%	1.4%
1	Water3	0.5%	0.9%
1	Water5	0.3%	0.6%
1	Lung9	1.2%	-0.8%
1	Bone10	-2.3%	-2.2%
2	Water1	1.7%	-2.1%
3	Water3	0.4%	1.4%
4	Water5	0.7%	-0.2%
4	Lung6	0.1%	0.5%
4	Bone10	-3.0%	-2.6%
5	Water2	1.4%	0.7%
5	Lung7	-0.3%	-0.5%
6	Water3	1.5%	0.5%
6	Bone10	-0.2%	-0.1%
7	Water5	2.0%	0.0%
8	Water5	1.1%	-0.3%

Table 11 Comparisons between M3D calculations and both point dose measurements and TPS calculations using AAA for TrueBeam 15MV for the IAEA-TECDOC-1583 cases.

Case	Position	[TB] 15MV Measured	[TB] 15MV AAA
1	Water1	0.1%	0.5%
1	Water3	0.8%	0.9%
1	Water5	0.4%	0.4%
1	Lung9	0.4%	-1.2%
1	Bone10	-3.4%	-0.8%
2	Water1	1.4%	-0.6%
3	Water3	1.4%	1.4%
4	Water5	0.9%	0.1%
4	Lung6	1.9%	1.3%
4	Bone10	-2.7%	-1.4%
5	Water2	1.1%	1.2%
5	Lung7	-0.8%	-0.4%
6	Water3	2.9%	2.3%
6	Lung7	4.6%	3.2%
6	Bone10	-0.3%	-0.5%
7	Water5	0.8%	0.4%
8	Water5	0.4%	0.5%

Mobius Verification Phantom

60 Pelvis VMAT plans were calculated on the MVP in M3D using the built-in feature and an imported scan, which included the couch. **Figure *3*** shows a histogram of the difference between these two methods. There is a clear skew to the in-built feature over-estimating the dose, which is expected due to the lack of consideration of the couch. However, all in-built calculations were within ±1.0% of the actual calculation and mean deviation was 0.2%. It should be noted that only plans that did not require a move in the phantom to position a chamber in a suitable location were considered. Since a substantial number of the local plans required a move, only the locally scanned MVP was used for the remainder of this work.

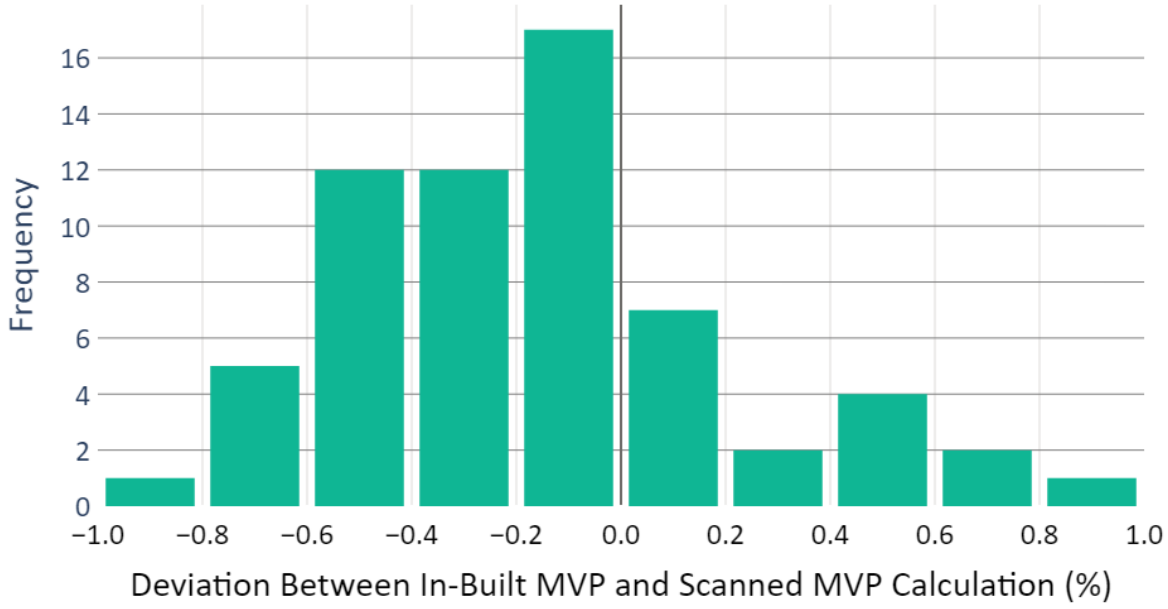

Figure 3 Histogram showing the difference between a M3D calculation reported mean dose to the ionisation chamber between the in-built MVP (excluding couch) and from the locally CT scanned MVP (including couch) (n=63). A negative deviation shows the locally scanned MVP reporting a lower dose.

DLG Correction

Halcyon

The DLG correction was found to be -0.89 mm and was applied for all further complex plan calculations. Since this value was derived based on clinical plans, only sites which were being treated clinically on the

Halcyon at the time were considered. These consisted primarily of urology plans, which are relatively simple in terms of MLC patterns. This work will need to be repeated for sites with more complex fields when they are considered (e.g., head and neck) to ensure the values remain valid.

TrueBeam

The initial M3D DLG correction was assessed for Breast IMRT fields. Values of –1.3 mm for 6MV and –1.8 mm for 15MV were determined and applied to all subsequent calculations. The only IMRT performed locally with 15MV are tangential breast fields for larger patients. However, as 6MV is utilised for VMAT, a further set of measurements were performed when transferring VMAT independent checks to M3D. 48 6MV VMAT plans were compared to determine whether the DLG was acceptable or required further adjustments. All measurements were within ±3% of the M3D calculated dose, with a skew to M3D overestimating the dose (see Figure 4). This was considered acceptable, and no further DLG correction adjustments were deemed necessary.

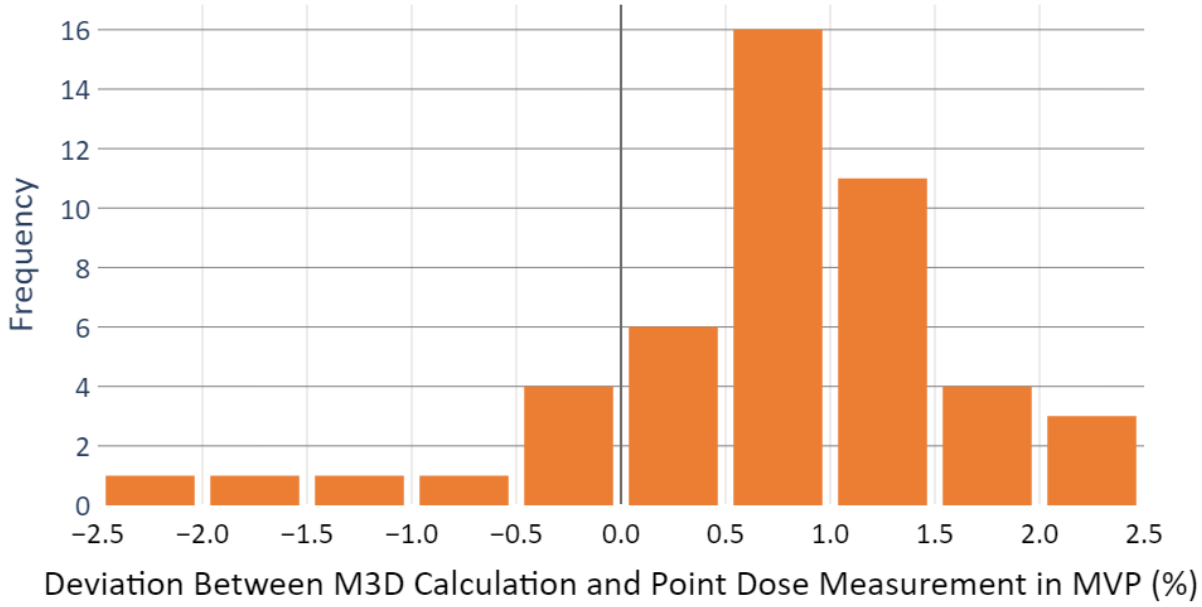

Figure 4 Histogram showing the difference in the MVP between a M3D calculation reported mean dose to the ionisation chamber and the dose physically measured at that point (n=48). A positive deviation shows the M3D calculation reporting a higher dose.

Clinical Plan Point Dose Measurements on Retrospective plan data

Halcyon

For the 60 previous clinical cases, the verification plan on the Mobius Verification Phantom (MVP) was exported to M3D and recalculated. These measurements were compared to the M3D calculated doses. All calculated values were within ±3% of the measured dose, with a mean deviation of –0.6% (M3D lower dose).

TrueBeam

For the breast IMRT plans there is skew to M3D calculating a higher dose than measurements. However, all are within ±2% with a mean deviation of 0.5%. For the VMAT plans there was a similar skew with all measurements within ±3% and a mean deviation of 0.7% (M3D higher dose).

Complex Plan Comparisons

Halcyon

For the Halcyon model, 183 clinical pelvic VMAT plans were considered in the comparison. All 183 plans had mean target deviations within ±2%. All plans had a gamma pass rate >98% for 5%/3mm criteria. Only 3 plans had a gamma pass rate <98% for 3%/3mm. Two of these were unusual breast cases and one rectum; all three had gamma pass rates of 99.9% or higher at 5%/3mm.

TrueBeam

For the TrueBeam model an initial cohort of 61 clinical breast plans were used for the assessment. These included 37 whole breast plans (IMRT), 11 boost plans (CRT) and 13 SCF plans (CRT).

For all the whole breast and boost plans the mean dose difference in the target was within ±3% for all but one plan, with a mean of -0.7%. Since the SCF plans do not use a target volume, only gamma comparisons were considered. The main gamma failure rates were in the lung area, with the TPS calculating increased dose in the lung. This is a limitation of AAA calculations, and when a sample was recalculated using AXB (Dose to Medium), the match was much improved.

Of the 61 plans, 32 had a gamma pass rate of 98% for 3%/3mm, with the lowest pass rate of the remaining 29 being 92.0%. Therefore, all plans meet the complex plan criteria suggested (5%/3mm pass rate of 90%). The failure regions tended to be in the lung close to the treated breast. This is a limitation of AAA calculations as it overestimates the scattered dose into the lung. Several plans were recalculated with AXB to determine whether this was the case. An example case is shown in **Figure *5*** . For the 4 cases calculated with both AAA and AXB, the mean dose difference changed from -1.7% to -0.8%.

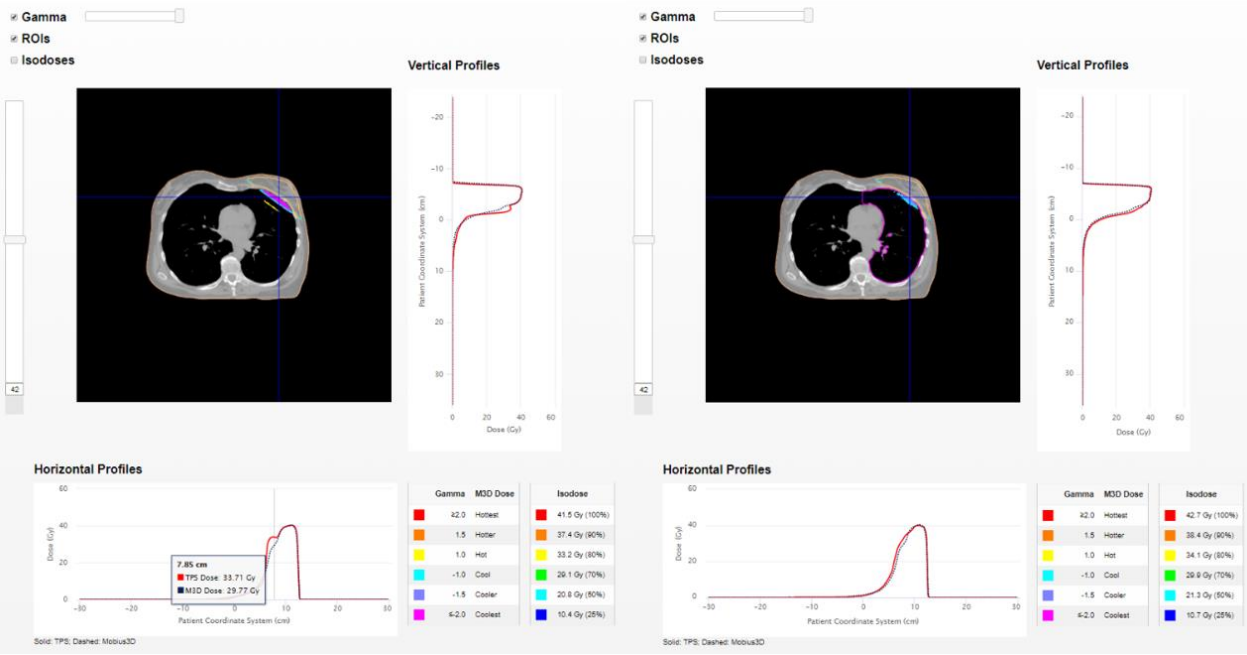

Figure 5 (AAA left; AXB right) Example of additional scatter to lung in AAA calculations compared to M3D and AXB calculations.

For the commissioning of M3D for VMAT on the TrueBeams, 136 plans were recalculated in M3D. The sites covered were Anal Canal (4), Brain (18), Colorectal (12), Gynaecological (19), Head and Neck (41), Lung (11), Upper GI (9), Urology (9) and other (13). The routine algorithm for each site was compared to M3D (i.e., AXB) using dose-to-water for lung, upper GI and other thorax plans, and AAA for all other sites). The 5%/3mm gamma pass rate was calculated for plans with 3%/3mm pass rate <95% and all passing rates were >90%. Histograms of Mean Combined Target Dose Difference (Figure 6) and Gamma Pass Rates (**Figure *7***) are shown below.

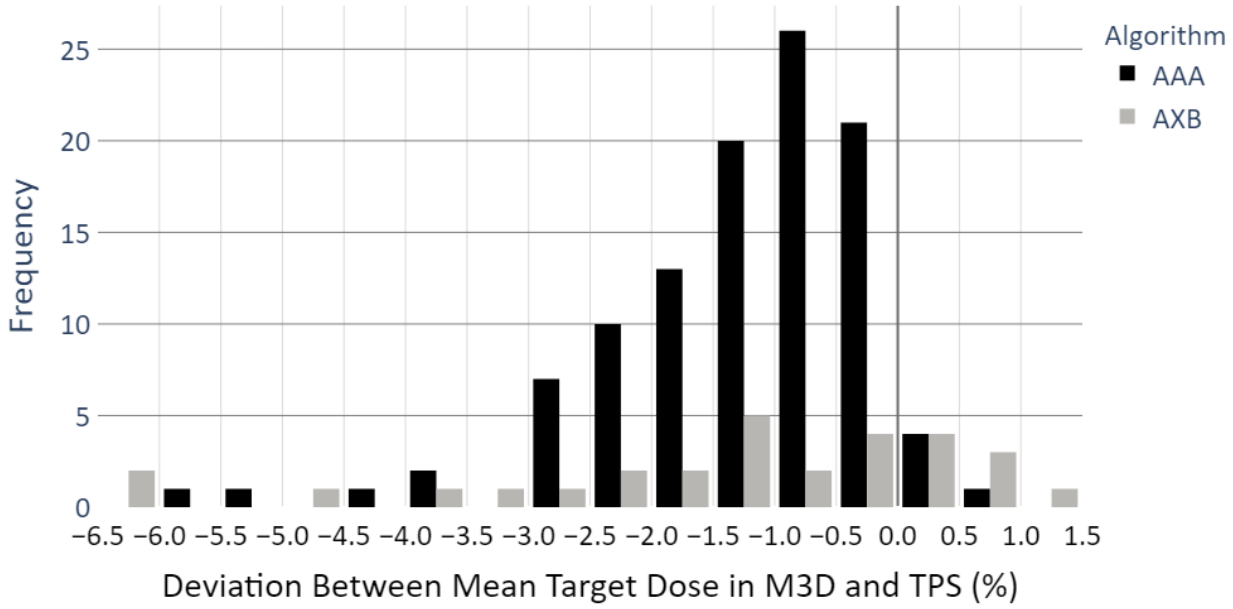

Figure 6 Histogram showing the difference in the mean target dose between the M3D calculation and the TPS dose for VMAT plans for two algorithms: AAA (black) (n=108) and AXB (Dose to Medium) (grey) (n=28). A negative deviation shows the M3D calculation reporting a lower dose than the TPS.

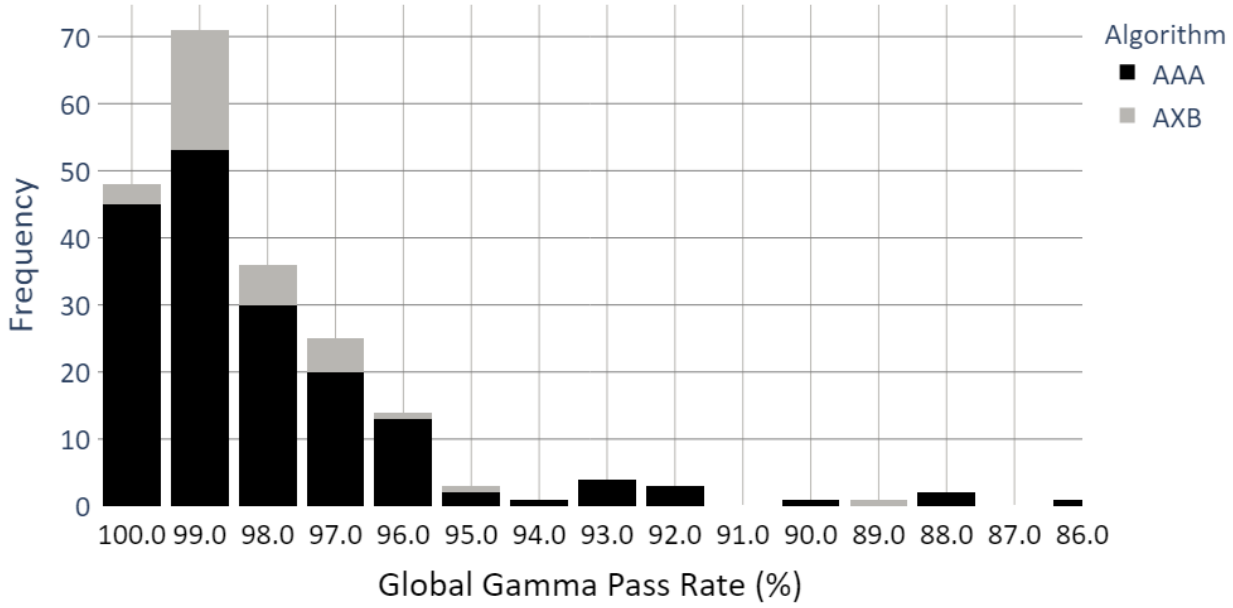

Figure 7: Global gamma pass rate (3%/3mm, 10% max dose threshold) for VMAT plans on conventional linacs for AAA (black) (n=176) and AXB (grey) (n=35). A single gamma value of 71.3% for

AAA is not included in the graph. x-axis values represent the middle of the bin e.g., the 99.0% value represents 98.5% to 99.4% inclusive, with all values rounded to one decimal place.

Four cases fell outside the expected accuracy of M3D:

- H&N: A nose treatment, with a narrow PTV at the surface with bolus. Significant inhomogeneity and very small, superficial PTV;
- Brain: Pituitary, proximal to sinuses. Significant inhomogeneity;
- Thorax: T2 Spine, proximal to lung. Significant inhomogeneity;
- Internal Mammary Chain (IMC): proximal to sternum and lung in the chest wall. Significant inhomogeneity and reduced scatter conditions;

It should be noted that the first three cases were calculated with AAA. When recalculated with AXB (Dose-to-Medium), all 3 were within the expected performance range. The only plan which continued to exceed these tolerances was the last IMC plan. This plan also failed the original independent calculation using Compass (IBA Dosimetry) when the plan was originally produced. Consequently, the original plan was escalated to additional measurements.

Clinical Workflow

The current clinical workflow was established during Phase 1 (Halcyon Pelvis VMAT) and 2 (C-Arm Breast IMRT and CRT) of the rollout and has been maintained for Phase 3 (C-Arm VMAT) and as such is applicable for all plan types treated locally.

The M3D calculation is performed as part of the Check task, in the care path. The flowchart in Fig [reference] describes this overall workflow. Locally, an Eclipse Scripting API (ESAPI) script has been produced to allow the user to interrogate the M3D database without navigating out of the ARIA environment. Further details on the ESAPI script are given below.

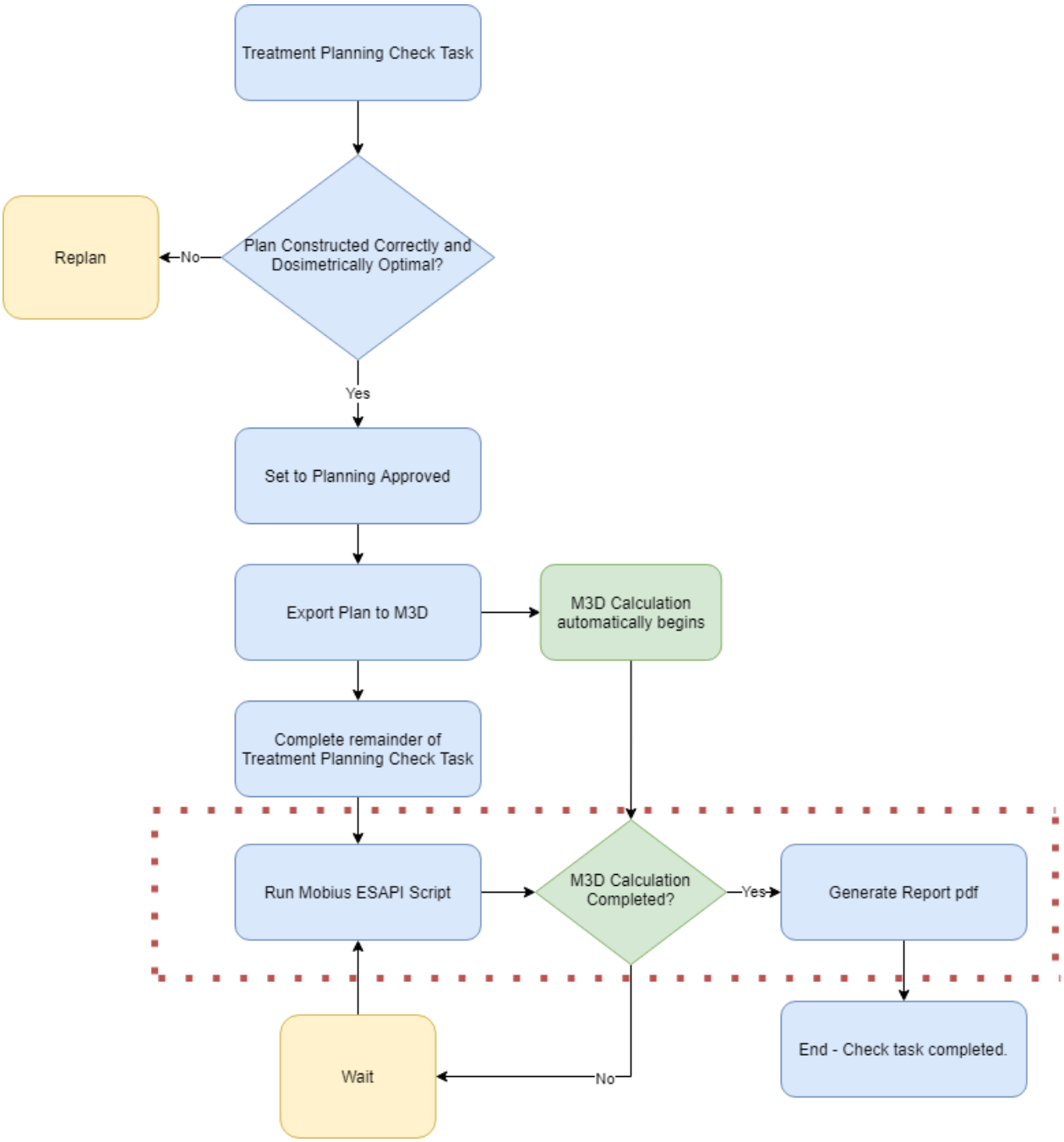

Figure 8 Clinical Workflow for M3D in our clinic. The running of the script and generation of the report (shown by the red dotted line) is described in further detail in the Scripting Workflow section below (Figure 9).

Tolerance Classifications

In order to provide stratification of treatment plans each plan type has three separate action levels that the calculation is evaluated against. These are:

- Level 1 – within locally defined expected performance (3%/3mm gamma calculation);
- Level 2 – within manufacture specified expected performance (5%/3mm gamma calculation);
- Level 3 – exceeds expected performance. Plan rejected or escalated to other QA.

Locally we have defined three separate types of plan types: simple, complex and an intermediate category for breast sliding window IMRT. Simple plans include parallel opposed pairs and conformal radiotherapy. Complex plans are VMAT plans. Each of these three categories have separate Level 1 and Level 2 tolerances. These are shown in the Table below. Due to the known issues mentioned above with areas of gamma failing in the lung region for breast IMRT, for these plan types the target Gamma Passing Rate (GPR) is considered suitable to use in the event that the body GPR exceeds the tolerance for a Level 1 calculation.

Table 12 Level 1 and Level 2 Tolerances for Level 1 and Level 2 for three different plan types. Tolerances are given for gamma passing rate (GPR) and mean dose difference (MDD). The target is defined as a structure that contains all the PTVs*PTVs (Planning Target Volume)*

Level	Simple	Breast Sliding Window IMRT	Complex
Level 1 (gamma 3%/3mm)	Body GPR ≥ 95% Target MDD ± 2%	Body GPR ≥ 95% OR Target GPR≥ 95% Target MDD ± 2%	Body GPR ≥ 95% Target MDD ± 3%
Level 2 (gamma 5%/3mm)	Body GPR ≥ 98% Target MDD ± 2%	Body GPR ≥ 98% Target GPR≥ 98% Target MDD ± 3%	Body GPR ≥ 90% Target MDD ± 5%

Scripting Workflow

Although different plan types have different tolerances, the workflow has been designed to remain the same through the use of an ESAPI and Python script. This workflow (expanded from Fig. Above) is shown below. It is worth explicitly noting that M3D can generate a default pdf report. This script was created locally to both generate a PDF report that had only the relevant data to our local tolerances and to also allow generation of this custom report without leaving the ARIA environment.

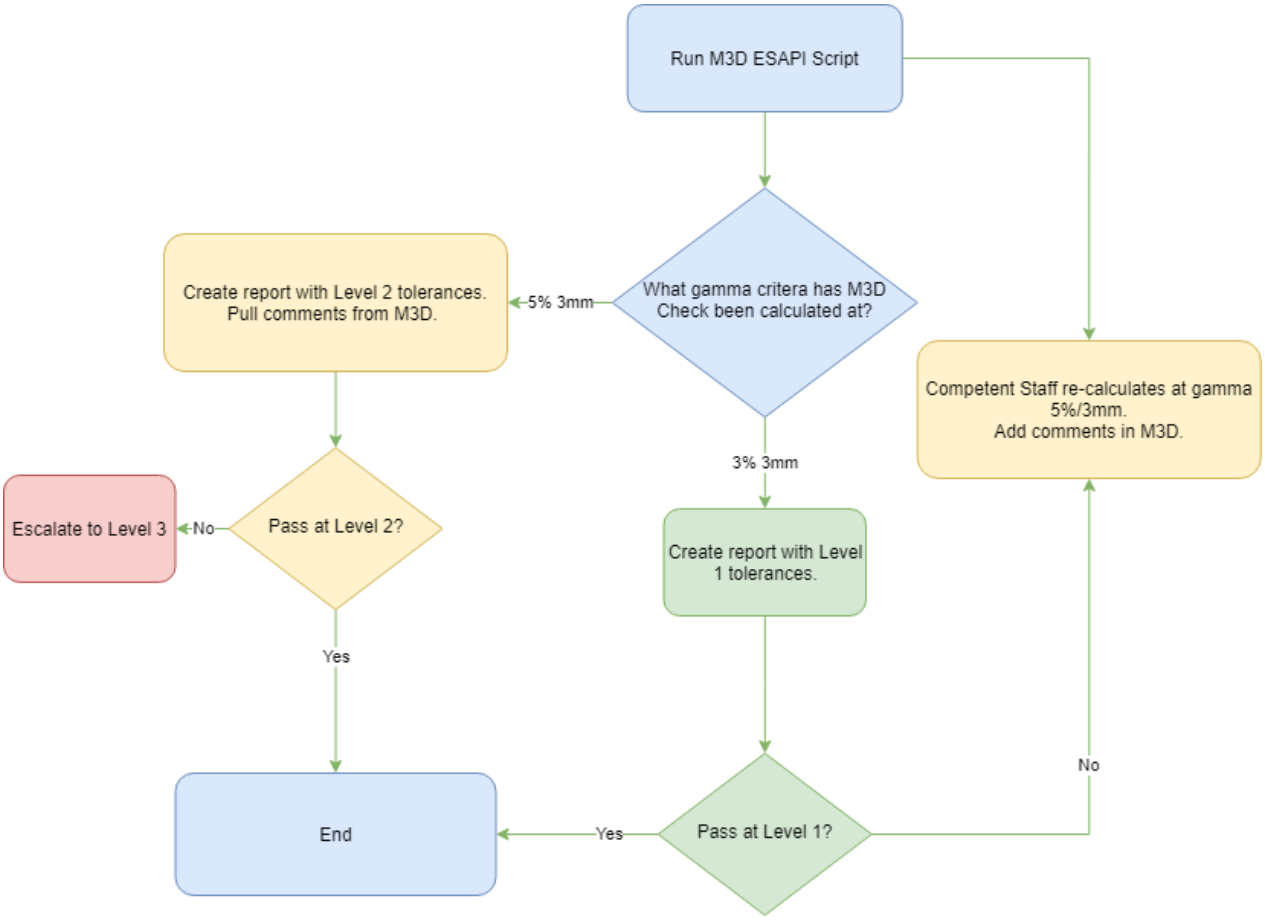

Figure 9 Overview of the ESAPI script operation and report generation.

The ESAPI script performs an assessment of the plan type based upon the MLC motion type the plan i.e., static, dose dynamic or VMAT. This allows the correct plan type tolerances to be applied. The ESAPI script also determines the value at which the gamma calculation has been performed, using this information to apply the correct tolerance Level.

A top-level view of the code is given in **Figure *10***.

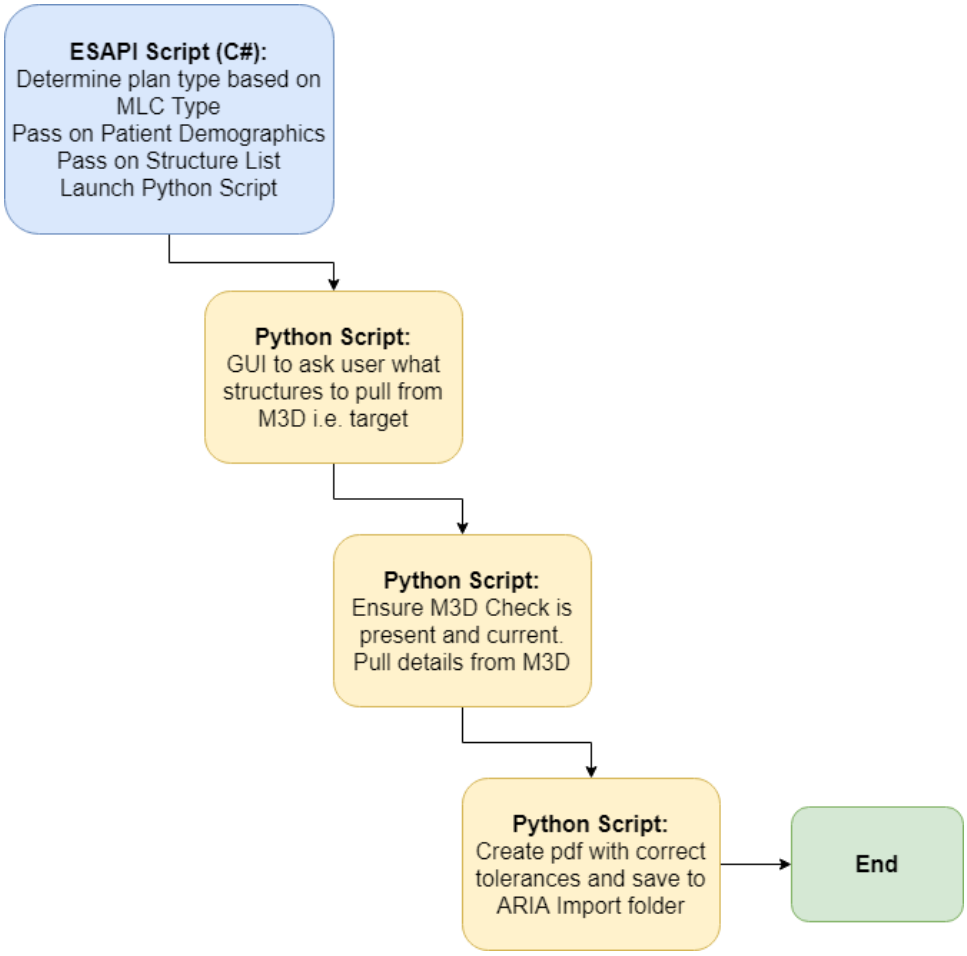

Figure 10 Top Level view of ESAPI and Python Script Logic Flow

Provided all steps have completed successfully, the script will generate a custom PDF report in our local ARIA document import folder. The user can then import this document as usual and assess the tolerances before approving or escalating as appropriate. An example of the custom pdf report is given in Appendix 1

Workflow efficiencies

Implementation of the above workflows has provided substantial workflow efficiencies. These stem from both the ability for M3D to begin calculations automatically when receiving DICOM data from the TPS and the ability to retrieve the plan report without leaving the ARIA environment. From timing studies, the approximate median time to perform PSQA of this type using our clinic's previous methodology was 9 minutes. For a level 1 M3D pass the median time is 1 minute, with a Level 2 taking a

similar amount of time to the previous methodology i.e., 9 minutes. Level 3 passes are assessed on a case-by-case basis and were not considered in the timing audit.

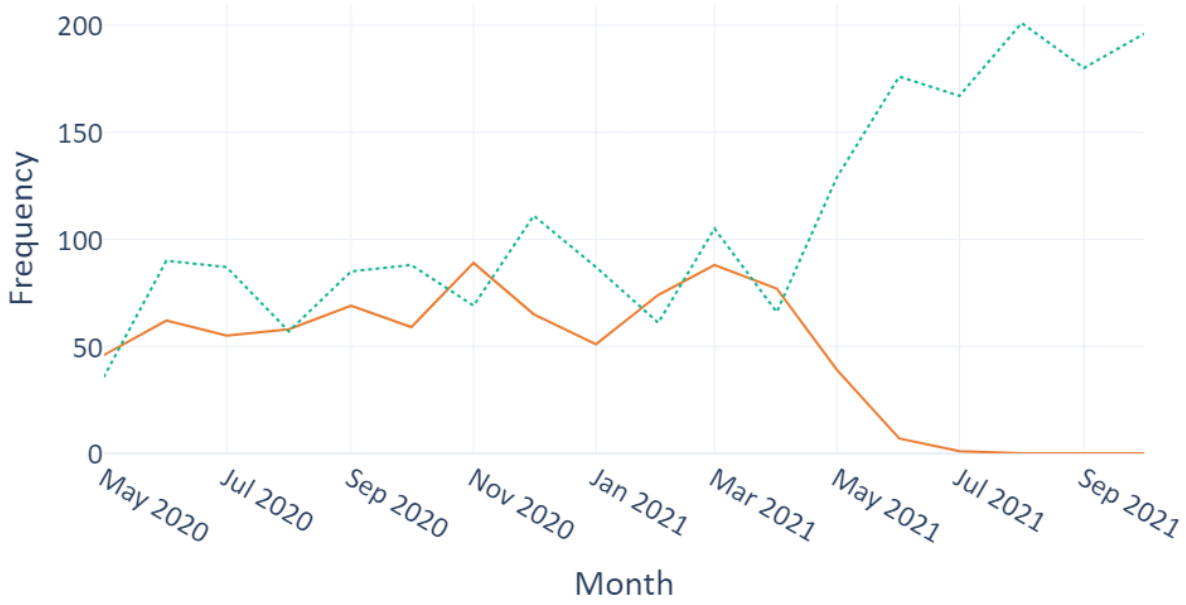

Figure 11 Local activity data for the amount of PSQA type performed by month. M3D Calculations are dashed green, with the previously used PSQA method shown in solid orange.

Using local activity data, the median number of independent calculations performed per month since May 2020 is 150. Over this period, 91% of M3D plans have passed at Level 1. As such, we estimate approximately 18 hours of staff time is saved per month from the efficiency savings gained using M3D and the described workflows.

System Maintenance

Appropriate quality assurance for software used within radiotherapy depends on the local working practices. A local risk assessment found that QA should be targeted specifically at changes to software or hardware, rather than performed periodically. For M3D this would be at software upgrades, changes to the server or when the local Record and Verify system (ARIA) is upgraded.

The functionality tests involve:

- Export of a range of plan types from ARIA. Does M3D correctly identify and automatically calculate the plans?
- If MobiusFX or MobiusCBCT is utilised the export of log files (of all types used locally) and CBCT would be exported to M3D to ensure they are identified and processed;
- All Scripts that interact with M3D would be run to ensure functionality. These would be run on plans exported to M3D pre and post upgrade.

Dosimetric tests would involve exporting to M3D a battery of previous patients that include all treatment types normally considered. The calculation results can be compared to previous performance to demonstrate that no undocumented changes have occurred. If dosimetric differences are expected additional plans should be assessed. These would be selected based on the documented changes. For example, if changes to static IMRT calculations are expected, additional IMRT plans would be assessed. If the handling of material densities were changed, additional plans with significant inhomogeneity would be assessed, along with comparisons to measurements in an inhomogeneity phantom (such as the IAEA tests included in the commissioning work).

As DICOM data sets are deleted from the server automatically, consideration of data storage is restricted to the result reports. M3D is not a data archive and records of performed quality assurance must be retained as required. The server has storage available for all data related to patient under treatment. The general practice locally is to store a record of the M3D calculation in the patient record on ARIA, which acts as the primary record of the independent calculation. Then the M3D record is maintained to allow for population data studies. If performance of the M3D server deteriorates, the old records will be removed, however that limit has not been reached yet. Currently there are 665 patients recorded in the local M3D database, with most patients having 1 or 2 plan calculations.

Discussion and Future Work on Mobius3D

Currently scripting is used on a patient-by-patient basis to provide customised reports. However, with minimal changes the script could be altered to extract large data sets for auditing purposes. For example, it may be possible to perform population data studies to determine if there has been a change in performance, either due to changes in staff or planning practices, new CT scanners or other equipment, etc. It may also be used to automatically collate data to perform pre- and post-upgrade standardized QA. In v4.0 of M3D Plan Types have been introduced to allow for additional customization

of assessment criteria. A Plan Type has certain triggers such as Plan ID, Machine and Fractionation (limited to 1, 3, 5 fractions or conventional fractionation). Each Plan Type can have specific assessment criteria, such as Gamma Criteria and passing rates and Organ at Risk (OAR) criteria. If local OAR criteria vary by site and/or fractionation, this may be included in the Plan ID (e.g., HeadNeck66 or HeadNeck55) and then the correct tolerance will be assigned (e.g., SpinalCordPRV 50Gy or 45Gy). Currently a simplified system is used locally, with no OAR specific assessment. With this additional feature we may look at implementing additional Plan Types to allow for this more detailed comparison. It would require a minor change in local practice in terms of naming conventions. This would allow for more tailored acceptance criteria, allowing for the identification of exceptions without triggering substantial number of false positives.

M3D v4.0 also introduces dose calculations on CBCT acquired during treatment sessions. M3D will calculate a dose distribution and provide the mean dose differences for each structure. The use of the feature requires the export of the CBCT images and the registration object. On receipt, M3D will automatically calculate the dose distribution. The use of the feature as an adaptive review is being considered. Currently, plans are referred to Physics by treatment staff if changes in the patient anatomy is observed. Physics will investigate whether the anatomical changes will result in significant dosimetric differences. This process is very time consuming, and most cases only result in minor changes. An automated system, which may be used to cut down the number of investigations required by Physics, would be a significant efficiency improvement and allow more time to be dedicated to viewing the cases where changes are significant.

Thoughts on the Future of QA

In radiotherapy, there has been a continual requirement to provide assurance that the patients' treatment is delivered as planned, as a surrogate to validating dose delivery to defined target and OAR. The relevance of this surrogate has become less so with increasing complexity of planning, imaging, and delivery systems, though remains the current practice for most Radiotherapy platforms.

Traditionally, the key requirement for classical radiotherapy has been to assure the treatment plan is accurate and deliverable. This has been achieved via pre-treatment measurement and often computer simulation recalculation, as provided by the M3D system. However, there is an emerging requirement to validate the quality of dose delivered to the OAR and target structures as the move to personalized, on-table adaptive radiotherapy is contemplated. This will see new demands for verification and validation

systems; a requirement to take information from multiple sources and then collate the available information. For example; volumetric patient imaging, exit portal fluence and linac log files must all be considered in producing the individual fraction-based validation and, with the addition of sophisticated dose aggregation algorithms, treatment dose may then be assured over the entire episode of care.

Conclusions

This whitepaper discusses the commissioning of M3D for clinical use for Halcyon and C-Arm linacs. This has been performed for VMAT, Conformal RT and Virtual Simulation treatment techniques. Commissioning work has demonstrated acceptable accuracy and known limitations of M3D were quantified. We have also incorporated M3D fully into our clinical workflow. This has streamlined our patient specific QA process, removing the need for measurement for the majority of cases. Plans requiring higher level of scrutiny are identified and stratified. Furthermore, the workflow of using M3D has been automated which has allowed for time saving efficiencies, and hence staff resource savings, in our patient pathway.

Overall, this work and M3D has benefited the patients receiving radiotherapy at Hull University Teaching Hospitals NHS Trust.

Reference

JAMES, H., BEAVIS, A., BUDGELL, G., CLARK, C., CONVERY, D. & MOTT, J. 2008. Guidance for the Clinical Implementation of Intensity Modulated Radiotherapy. Report No. 96. York, UK: IPEM.

TECDOC, I. 2008. 1583: commissioning of radiotherapy treatment planning systems: testing for typical external beam treatment techniques. *Vienna: International Atomic Energy Agency*.

Appendix 1: Example Custom Report

Hull University Teaching Hospitals NHS Trust

Mobius Report Summary

Patient ID	HEY[redacted]
Name	[redacted]
DOB	[redacted]
Course	1LTBREAST
Plan	LTBREAST
Planning Approved:	10 Feb 2021 11:15:23

Gamma Results

ROI	Gamma	Tolerance	Mean Diff	Tolerance
PTV WB	n/a	n/a	-0.28 %	±2%
Body	99.2%	≥95%	n/a	n/a

Gamma Criteria

Criteria	Reference Dose	Threshold Dose
3.0%/3 mm	27.6 Gy (Max Dose)	2.76 Gy