Commissioning and clinical implementation of Mobius3D and MobiusFX: Experience on multiple linear accelerators

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Abstract

Purpose: To provide practical guidelines for Mobius3D commissioning based on experiences of commissioning/clinical implementation of Mobius3D and MobiusFX as patient-specific quality assurance tools on multiple linear accelerators.

Methods: The vendor-suggested Mobius3D commissioning procedures, including beam model adjustment and dosimetric leaf gap (DLG) optimization, were performed for 6 MV X-ray beams of six Elekta linear accelerators. For the beam model adjustment, beam data, such as the percentage depth dose, off-axis ratio (OAR), and output factor (OF), were measured using a water phantom and compared to the vendor-provided reference values. DLG optimization was performed to determine an optimal DLG correction factor to minimize the mean difference between Mobius3D-calculated and measured doses for multiple volumetric modulated arc therapy (VMAT) plans. Small-field VMAT plans, in which Mobius3D has dose calculation uncertainties, were initially included in the DLG optimization, but excluded later.

Results: The measured beam data were consistent across the six linear accelerators. Relatively large differences between the reference and measured values were observed for the OAR at large off-axis distances (>5 cm) and for the OF for small fields (<3 × 3 cm²). The optimal DLG correction factor was 0.6 ± 0.3 (range: 0.3–1.0) with small-field plans and 0.2 ± 0.2 (0.0–0.5) without them.

Conclusions: A reasonable agreement was found between the vendor-provided reference and measured beam models. DLG optimization results were dependent on the selection of the VMAT plans, requiring careful attention to the known dose calculation uncertainties of Mobius3D when determining a DLG correction factor.

1. Introduction

Dose-volume histogram (DVH)-based patient-specific quality assurance (QA) has replaced conventional hardware-based patient-specific QA [1–3]. DVH-based patient-specific QA has several advantages over its phantom-based counterpart. First, DVH-based methods calculate dose distributions on patient geometry, which considers tissue heterogeneity, not on a simple geometry with uniform density. Moreover, such methods provide information on potential causes for patient-specific QA failure, e.g., a multileaf collimator (MLC) positional error, measured using either machine log files or an electronic portal imaging device. Performing more clinically relevant dosimetric comparisons using the DVH is another advantage of software-based patient-specific QA methods.

Mobius3D and MobiusFX, which are commercial software packages for DVH-based patient-specific QA, have been evaluated in previous studies [4–12]. Mobius3D is designed to perform an independent verification of a treatment planning system (TPS) dose by calculating the dose using its own algorithm. This procedure is referred to as the “plan check” by the vendor. MobiusFX calculates the dose using the Mobius3D dose calculation algorithm; however, it incorporates further information, which is recorded in log files during the delivery of the plan. The log files include data regarding the MLC position, gantry/collimator angles, and monitor units. The MobiusFX-calculated dose is subsequently compared to the TPS-calculated dose, replacing the phantom-based measurement. This procedure is referred to as the “QA check” by the vendor. Automated dose calculation using Mobius3D (plan check) can improve clinical efficiency for patient-specific QA because it is automatically triggered upon the receipt of a set of DICOM files (computed tomography (CT), radiation therapy (RT) structure, RT plan,
RT dose). In addition, the QA check is automatically performed once a patient plan is delivered by a treatment machine and a corresponding treatment log file is transferred to the software server.

Evaluating the accuracy of Mobius3D and MobiusFX is of particular importance since dosimetric verification using a software-based patient-specific QA system is performed without measuring the radiation dose. There have been efforts toward validating the clinical feasibility of using Mobius3D for independent verification of the TPS dose [4–7]. Evaluations of the accuracy of MobiusFX have been recently conducted in several studies [8–11]. A previous study by Kim et al. showed that dose calculation uncertainties exist for small fields in Mobius3D, even with a finely tuned dosimetric leaf gap (DLG) correction factor [12]. The DLG correction factor in Mobius3D adjusts MLC opening width, thereby controlling the overall level of the resulting dose. It is noted that the DLG correction factor should not be considered as an actual DLG value in the six Elekta linear accelerators were beam-matched and a common beam model is in clinical use. The measured PDD, OAR, and OF values were loaded onto Mobius3D to replace the vendor-provided reference values. It is noteworthy to mention that Mobius3D is capable of optimally fitting the beam model to the user-provided beam data as demonstrated in Nelson et al. [5]. Upon the submission of the measured PDD, OAR, and OF values, Mobius3D performs an automatic adjustment of beam model parameters, which are related to energy spectrum, jaw transmission, MLC tip design, scattering filter characteristics, off-axis softening, source size, and electron contamination, so that the fine-tuned beam model best matches to the measured beam data.

2. Methods and materials

2.1. Overview

Mobius3D and MobiusFX version 2.1.2, which are patient-specific QA software packages (Varian Medical Systems, Palo Alto, CA, USA), were commissioned and clinically implemented for six Elekta linear accelerators (Elekta, Stockholm, Sweden): four Infinity and two VersaHD linear accelerators, which were all equipped with Agility MLCs. Mobius3D was commissioned only for 6 MV flattened X-ray beams, which are currently used to treat most patients via VMAT.

Mobius3D commissioning comprises five steps: (1) verification of the machine output calibration factor, (2) verification of the beam modeling, (3) verification of the CT-to-density table, (4) open field test, and (5) verification of the Mobius3D dose calculations on patient plans; the final step may simply be referred to as DLG optimization since, depending on the results of the step, the DLG correction factor may require adjustment. Among the aforementioned commissioning steps, the following subsections will describe the details of two steps: verification of the beam modeling (Section 2.B) and DLG optimization (Section 2.C). The last sub-section (Section 2.D) will describe the clinical implementation of Mobius3D and MobiusFX.

2.2. Mobius3D commissioning: Verification of the beam modeling

Mobius3D allows users to customize the vendor-provided beam model by replacing the reference percentage depth dose (PDD), off-axis ratio (OAR), and output factor (OF) values with measured data. To verify the Mobius3D reference beam modeling, PDD, OAR, and OF for each of the six Elekta linear accelerators were measured using a PTW BeamScan water phantom and a PTW microDiamond detector (PTW, Freiburg, Germany) at the vendor-specified measurement conditions. PDD was measured at depths of 5, 15, and 25 cm with a source-to-surface distance (SSD) of 100 cm for each of the square fields with sizes of $5 \times 5$, $10 \times 10$, and $20 \times 20$ cm$^2$. OAR was measured at off-axis distances of $1, 2.5, 5, 7.5, 10, 15, 20$, and at a depth of 5 cm with an SSD of 100 cm. OF was measured at a depth of 10 cm with an SSD of 90 cm for various field sizes: $2 \times 2, 3 \times 3, 5 \times 5, 10 \times 10, 15 \times 15, 20 \times 20, 25 \times 25, 30 \times 30, 34 \times 34$, and $40 \times 40$ cm$^2$. The OF values, which were measured at the time of beam commissioning and were used for the beam modeling in treatment planning system, were used without further measurement. Therefore, the OF values of three groups of beam models were used: (1) linac 1, 4–5, (2) linac 2–3, and (3) linac 6. For each of these three groups, the linear accelerators were beam-matched and a common beam model is in clinical use. The measured PDD, OAR, and OF values were loaded onto Mobius3D to replace the vendor-provided reference values. It is noteworthy to mention that Mobius3D is capable of optimally fitting the beam model to the user-provided beam data as demonstrated in Nelson et al. [5]. Upon the submission of the measured PDD, OAR, and OF values, Mobius3D performs an automatic adjustment of beam model parameters, which are related to energy spectrum, jaw transmission, MLC tip design, scattering filter characteristics, off-axis softening, source size, and electron contamination, so that the fine-tuned beam model best matches to the measured beam data.

2.3. Mobius3D commissioning: DLG optimization

To perform the DLG optimization, 12–21 patients (median: 15) were selected so that these cases can proportionally represent the patient population who are treated by each of the six Elekta linear accelerators based on tumor site. To this end, the selection of plans was based on the statistics of the plans treated over past several months. The characteristics of the patients selected for each linear accelerator are summarized in Table 1. For the DLG optimization, an optimal DLG correction factor was determined to minimize the mean point dose error $\tilde{\epsilon}$, which is defined as:

$$\tilde{\epsilon} = \frac{1}{N} \sum_{i=1}^{N} \frac{(D_{\text{MED}} - D_{\text{meas}})}{D_{\text{meas}}},$$

where $D_{\text{MED}}$ and $D_{\text{meas}}$ represent the Mobius3D-calculated and ionization chamber-measured point doses, respectively, and $N$ represents the number of patients considered for the DLG optimization. The patient VMAT plans were calculated using Mobius3D and measured on ArcCHECK (Sun Nuclear, Melbourne, Florida, USA) with an A1SL ionization chamber (Standard Imaging, Middleton, WI, USA) inserted into the phantom center. The entire region of the ArcCHECK phantom was overruled to a density of 1.15 g/cm$^3$, which was determined via a series of verification tests. To reduce measurement uncertainties, the cavity

<table>
<thead>
<tr>
<th>Tumor site</th>
<th>Number of patients</th>
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<tr>
<td>Linac 1</td>
<td>Linac 2</td>
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<tr>
<td>Bone</td>
<td>3</td>
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<tr>
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<td></td>
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<tr>
<td>Breast</td>
<td>3(2)</td>
</tr>
<tr>
<td>Cervix</td>
<td>1</td>
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<td>Esophagus</td>
<td>1</td>
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<tr>
<td>Liver</td>
<td>1</td>
</tr>
<tr>
<td>Lung</td>
<td>5(1)</td>
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<td>1</td>
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<td>Thyroid</td>
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<tr>
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<td>Total</td>
<td>15(3)</td>
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Table 1 Characteristics of the VMAT plans selected for the DLG optimizations for the six linear accelerators. The number of VMAT plans, for which the ratio of the dose change to the change in the DLG change factor was $\geq 3$% and which, therefore, were excluded later from the DLG optimization, was represented in parenthesis.
volume of the ionization chamber was located in regions with low dose gradients. The Mobius3D-calculated dose was calculated as the mean dose over the chamber cavity volume (0.053 cm$^3$).

The Mobius3D DLG optimization can be mathematically formulated as an optimization problem that determines an optimal DLG correction factor $C_{DLG}^*$ to minimize the mean point dose error as follows:

$$C_{DLG}^* = \min_{C_{DLG}}(\Delta C_{DLG})$$

(2)

The radiation doses to the ArcCHECK phantom as per the patient VMAT plans were calculated for various DLG correction factors between −0.5 and 1.0 with an interval of 0.5. Following the vendor-provided procedures, a linear regression analysis was performed to determine the best-fit curves for the linear relationship between the mean point dose error and the DLG correction factor.

Mobius3D dose calculation uncertainties exist for small fields as reported in previous studies [10,12]; thus, the impact of the dose calculation uncertainties should be considered so that they do not affect the DLG optimization results. Specifically, dose underestimation for small fields by the Mobius3D calculation algorithm can result in an overestimated DLG correction factor when small-field VMAT plans are included in the DLG optimization plan set. To facilitate an appropriate selection of VMAT plans for the DLG optimization, the field size collimated by the MLC can be calculated, for instance, in terms of the mean MLC opening. Alternatively, a surrogate measure, which is highly correlated with the field size, can be calculated; in this study, the ratio of the dose change to the change in the DLG correction factor ($\Delta D_{MEAS}/\Delta C_{DLG}$) was calculated. A Pearson correlation analysis was performed for the VMAT plans selected for the DLG optimization of one linear accelerator with the largest number of VMAT plans (linac 5) to examine the relationship between $\Delta D_{MEAS}/\Delta C_{DLG}$ and the mean MLC opening width, which were calculated for each of the patients. The rationale behind this correlation analysis can be described as follows. The effect of the DLG correction factor on the resulting dose may depend on the field size (or MLC opening width). For example, a change in the DLG correction factor may have a more substantial influence on smaller fields. This correlation analysis was conducted using MATLAB (MathWorks, Natick, MA, USA), resulting in a Pearson correlation coefficient $r$ and corresponding p-value $p$, which were calculated with a 95% statistical confidence. The mean MLC opening width was calculated by averaging the distances between the two leaves across all open MLC leaf pairs for all beam segments using an in-house program based on MATLAB.

The DLG optimization was conducted for two different sets of VMAT plans: (1) all the representative VMAT plans (Table 1) and (2) all VMAT plans except small-field plans. The number of small-field VMAT plans, which were excluded from the DLG optimization, was represented in parenthesis in Table 1. To eliminate small-field plans, a tolerance of $\Delta D_{MEAS}/\Delta C_{DLG} \leq 3\%$ was applied as an alternative method, instead of a tolerance that is directly related to the field size.

### 2.4 Clinical implementation

Upon completion of the commissioning of Mobius3D, MobiusFX was clinically implemented for the pretreatment VMAT delivery verification, which was conventionally conducted using physical phantoms. In other words, the resulting dose, which was calculated by the Mobius3D dose calculation algorithm using the log information, replaced the measured dose in this DVH-based QA method. To facilitate a “point dose” comparison, similar to that in the conventional phantom-based patient-specific QA method, a spherical structure with a radius of 0.25 cm was created in high dose regions with low dose gradients. The mean dose over this volumetric structure was compared to that calculated using the treatment planning system in clinical use, RayStation (RaySearch Laboratories, Stockholm, Sweden); a point dose error was defined as the difference in the mean dose over the spherical structure between the MobiusFX- and RayStation-calculated doses. The overall dose distributions calculated by MobiusFX and RayStation were compared using a three-dimensional gamma analysis algorithm in MobiusFX; an absolute global gamma analysis was performed with 3%/3 mm criteria and 10\% dose threshold. The pass/fail criteria were that the point dose error should be less than 5\% and the percentage of passing gamma (gamma passing rate) with 3%/3 mm tolerances should be higher than 90\%. If one of the criteria was not met, the ArcCHECK-based measurement was performed for further verification.

MobiusFX was commissioned and clinically implemented for VMAT plans with an X-ray energy of 6 MV. During a period of three months (Nov/2019–Jan/2020), MobiusFX-based patient-specific QA was performed for 661 patient VMAT plans in total. Statistics of the patient-specific QA results, such as the number of passes/failures, the mean (and standard deviation) of the point dose errors, and gamma passing rates, were calculated. Furthermore, failure patterns of the patient-specific QA using MobiusFX were analyzed.

### 3 Results

#### 3.1 Mobius3D commissioning

Fig. 1 summarizes the differences between the measured and vendor-provided PDD, OAR, and OF values. As illustrated in Fig. 1 (a), the measured PDD values agreed with the reference PDD values at the depths of 5, 15, and 25 cm; the difference between the measured and reference PDD values was $\pm 0.2 \pm 0.5\%$ (range: $-1.2$ to 0.8\%) across all field sizes, depths, and linear accelerators. The maximum difference in the PDD values across the six linear accelerators was 1.2\%. Fig. 1 (b) compares the measured OAR values to the vendor-provided OAR values. The deviation of the measured OAR values from the reference values was within 1.5\% for an off-axis distance up to 5 cm. Relatively large differences between the reference and measured OARs were observed for off-axis distances > 5 cm. Overall, the Mobius3D 6 MV X-ray beam (reference) was observed to be flatter than the measured beams. The machine-to-machine variation of the OAR values showed a similar trend to the OAR difference between the reference and measured values. The maximum difference in the OAR values across the linear accelerators was smaller than 0.9\% for an off-axis distance up to 7.5 cm. Fig. 1 (c) presents the difference between the measured and vendor-provided OF values. The differences were within 1\%, except for the smallest field size ($2 \times 2$ cm$^2$), as illustrated in Fig. 1 (c). The OF values were observed to have small machine-to-machine variations, especially for fields $\leq 5 \times 5$ cm$^2$. The maximum difference between the OF values across the six linear accelerators was 0.2\% for these fields. For all field sizes, the maximum OF difference between the machines was 1.3\%.

Fig. 2 summarizes the DLG optimization results for the six linear accelerators, which were performed for all of the VMAT plans (Table 1), including small-field plans. In Fig. 2, the mean point dose errors are plotted against the DLG correction factors, between a range of −0.5 and 1.0 with an interval of 0.5, along with the linearly interpolated curves. The optimal DLG correction factor and the linear regression results (slope and R-squared ($R^2$)) are also provided in Fig. 2. A linear relationship between the DLG correction factor and mean point dose error was observed, evident from the value of $R^2 = 1.0$ for all linear accelerators. The slope of the linear-regressed curves ranged from 1.9 to 2.8, which corresponded to 1.9\% and 2.8\% increases in the Mobius3D-calculated dose, respectively, (on average across the patients) for an increase of 1.0 in the DLG correction factor. The optimal DLG correction factors varied across the six linear accelerators. The mean and standard deviation of the optimal DLG correction factors were 0.6 ± 0.3 (range: 0.3 to 1.0).

Fig. 3 illustrates the relationship between $\Delta D_{MEAS}/\Delta C_{DLG}$ and the mean MLC opening width for linac 5. The two variables were inversely proportional, as indicated by the negative value of the Pearson correlation coefficient ($r = -0.7$). Furthermore, this negative correlation
between $\Delta D_{\text{MED}} / \Delta C_{\text{DLG}}$ and the mean MLC opening width was found to be statistically significant ($p = 0.00$). The mean MLC opening width ranged from 1.3 to 4.9 cm. The results showed that the Mobius3D-calculated dose changed by 0.5–4.6% per unit change in the DLG correction factor.

Fig. 4 shows the DLG optimization results after the VMAT plans with $\Delta D_{\text{MED}} / \Delta C_{\text{DLG}} > 3\%$ were excluded from the DLG optimization. As summarized in Table 1, 1 to 5 VMAT plans were excluded from the original plan sets. It was not feasible to observe any tumor site-dependency of the number of the plans excluded due to small numbers of plans for each tumor site. Linear relationships between the mean point dose error and DLG correction factor were replotted in Fig. 4, similar to Fig. 2. The optimal DLG correction factors were $0.2 \pm 0.2$ (range: 0.0 to 0.5), showing overall decrease across the linear accelerators compared to the values shown in Fig. 2. In addition, the slopes of the linear-regressed curves reduced from $2.2 \pm 0.4$ to $1.7 \pm 0.1$ upon excluding the plans with a rapid change in the dose level.
3.2. Clinical implementation

Fig. 5 presents the statistics of the failure and pass cases based on the pretreatment VMAT verifications using MobiusFX. On average, 5.9% of the total VMAT plans (39 out of 661) failed to meet the criteria, requiring further verifications via phantom-based measurements. In Fig. 6, the pretreatment VMAT verification results using MobiusFX are further presented; the point dose errors and gamma passing rates are displayed as histograms. The point dose errors were 0.0 ± 2.5% and 97.9 ± 3.0%, respectively. The point dose error was less than −5% for 21 VMAT plans while no VMAT plan resulted in a point dose error >5%. All of the cases, in which the MobiusFX-based VMAT verification resulted in failure, passed the phantom-based verification tests.

Fig. 7 shows the results of the pretreatment VMAT verification performed using MobiusFX for a representative failure case. Although the ArcCHECK-based verification resulted in a point dose error of 0.8% and gamma passing rate of 97.0%, a large discrepancy was observed for this patient case, resulting in a point dose error of −8.6% and gamma passing rate of 86.9%.

4. Discussion

This study presents the Mobius3D commissioning and clinical implementation results of six Elekta linear accelerators. The commissioning results include the comparisons of the measured PDD, OAR, and OF values to the vendor-provided reference values. Since these beam data were measured on multiple Elekta linear accelerators, the comparisons across multiple machines can provide useful information regarding the extent to which the vendor-provided beam model represents Elekta linear accelerators in clinical use. Furthermore, the findings from the DLG optimizations, conducted on multiple linear accelerators, provide practical guidelines for the Mobius3D DLG optimization.

Different levels of agreement were found for PDD, OAR, and OF between the vendor-provided reference and measured values. First, the vendor-provided and measured PDD values were closely matched across all linear accelerators, indicating that the energy spectrum of the 6 MV X-ray beam in the Mobius3D dose calculation algorithm can be representative of those of Elekta linear accelerators. However, there was a difference in the level of beam flatness between the Mobius3D reference and measured (or actual linac) beams. These results indicate that the OAR values should be adjusted to improve agreement between the Mobius3D-calculated and measured doses, especially for relatively large off-axis distances (≥7.5 cm). Finally, the Mobius3D reference OF values were smaller than the measured OF values for small fields (2 × 2 cm²); the difference was >1%. Overall, only small deviations were observed for all the beam data, except the OARs for the fields >10 × 10 cm².

Small machine-to-machine variations of the PDD, OAR, and OF values were observed for the six Elekta linear accelerators. Although all the machines were not beam-matched to each other, the beam characteristics, which were measured for the Mobius3D commissioning, were closely matched, as shown in Fig. 1. Relatively large differences (>2%) across the linear accelerators were observed only for the OAR values for
the off-axis distances of 10, 15, and 20 cm. Therefore, similar beam delivery quality can be expected for all linear accelerators considered in this study for VMAT plans, in which most of the beam openings are covered by a field size of $15 \times 15 \text{ cm}^2$.

The resulting DLG correction factor values were influenced by the set of VMAT plans selected for the DLG optimization as can be observed by comparing Figs. 2 and 4. After eliminating the VMAT plans with $\Delta D_{\text{MED}}/\Delta C_{\text{DLG}} > 3\%$, the optimal DLG correction factor was reduced from $0.6 \pm 0.3$ (range: 0.3–1.0) to $0.2 \pm 0.2$ (0.0–0.5). A previous study reported that Mobius3D experiences dose calculation uncertainties (dose underestimation) for small fields $< 2 \times 2 \text{ cm}^2$, even with beam modeling refinement and adjustments made by the user [10]. Similar results were obtained for Elekta machines in a recent study by Kim et al. [12]. With the existence of dose calculation uncertainties for small fields, VMAT plans with small MLC openings should be excluded as conducted in this study. Calculating $\Delta D_{\text{MED}}/\Delta C_{\text{DLG}}$ is an alternative method to exclude such VMAT plans without directly calculating the MLC opening widths as a statistically significant negative correlation between the mean MLC opening width and $\Delta D_{\text{MED}}/\Delta C_{\text{DLG}}$ was established using the Pearson correlation analysis. Since $\Delta D_{\text{MED}}/\Delta C_{\text{DLG}}$ can be easily calculated using the Mobius3D-calculated doses with different DLG correction factors during the DLG optimization, the appropriate selection of VMAT plans can be facilitated using this measure. The DLG optimization with only slow-varying VMAT plans (or non-small field VMAT plans) with respect

Fig. 4. Results of the dosimetric leaf gap (DLG) optimizations for all six linear accelerators, where the optimizations were performed by excluding the VMAT plans with a Mobius3D-calculated dose change per unit DLG correction factor change $> 3\%$. The mean point dose errors are plotted against the DLG correction factors with the linear-regressed best-fit curves represented as solid lines. The optimal DLG correction factors are represented with asterisks. For each linear accelerator, the optimal DLG correction factor and linear regression results (slope and R-squared ($R^2$)) are also provided in the legend.

Fig. 5. Statistics of the pretreatment VMAT verification performed for the six linear accelerators over three months. The percentages of the failure/pass cases are graphically illustrated in the bar plots. The numbers of the failure/pass cases are also provided.
to the DLG correction factor will result in an optimal DLG correction factor that is not biased by the Mobius3D dose calculation uncertainties. Including small-field VMAT plans will result in an overestimated DLG correction factor as demonstrated in the results in Figs. 2 and 4.

With the optimal DLG correction factors that were obtained by excluding small-field VMAT plans, MobiusFX-based VMAT verification for small-field VMAT plans is more likely to fail to meet the criteria as demonstrated in the results in Figs. 2 and 4. Small variations in the optimal DLG correction factor (0.0 to 0.5) were observed across the six linear accelerators. The maximum difference in the optimal DLG correction factor across the linear accelerators was 0.5, and this value can be interpreted as 0.9% of the dose; the mean slope of the graphs, which represents the mean change in the Mobius-calculated dose with respect to the change in DLG correction factor in possibly due to dose calculation uncertainties for small fields. On the other hand, the ArcCHECK-based verification for these failure cases satisfied the criteria, further supporting the existence of dose calculation uncertainties.
Fig. 4 is 1.7%. There are several possible reasons for these variations across multiple linear accelerators. First, these variations may result from differences in the machines themselves. As shown in the comparisons of the beam characteristics such as PDD, OAR, and OF, the six Elekta machines may have different beam delivery characteristics. It is noteworthy that the beam characteristics (at least for 6 MV X-ray) of the six Elekta linear accelerators were relatively similar to each other. Second, for the DLG optimization for each machine, different VMAT plans (possibly with different levels of beam modulation complexity) were selected. To prevent the influence of the selection of VMAT plans on the optimal DLG correction factor, a standardized set of VMAT plans, which represent the clinical cases at an institute, can be developed as suggested in the report of the American Association of Physicists in Medicine (AAPM) Task Group 119 [13]. Finally, a small difference in the machine output may contributed to the machine-to-machine variation in the optimal DLG correction factor although the machine output calibration was performed on a monthly basis.

A similar optimal DLG correction factor may result from the DLG optimization at other institutions if the Elekta linear accelerator has similar machine output and beam characteristics to those presented in this study. The results of this study indicate that the optimal DLG correction factor may not greatly deviate from the range that resulted from the six Elekta machines at the authors’ institution.

It is crucial that the output of linear accelerator should be accurately calibrated for the commissioning and clinical implementation of Mobius3D and MobiusFX. First, since the Mobius3D DLG optimization matches the Mobius3D-calculated doses to the measured doses for patient VMAT plans, linac output calibration can influence the resulting DLG correction factor. Second, unlike hardware-based patient-specific QA methods, Mobius3D-based patient-specific QA does not incorporate the linac output into the corresponding dosimetric comparison results, such as the point dose error and gamma passing rate, as demonstrated in the previous study by Song et al. [8]. Therefore, accurate linac output calibration is a prerequisite for the successful implementation of a software-based patient-specific QA method.

The following guidelines for the commissioning of Mobius3D and clinical implementation of MobiusFX can be provided based on the results and discussions above.

- Fine-tuning of the Mobius3D PDD, OAR, and OF values may be required when an improved agreement is desired between the Mobius3D and measured beam characteristics. For Elekta linear accelerators (Synergy and VersaHD with Agility MLC), adjustment of PDD may not be necessary.
- Excluding small-field VMAT plans is desirable for the DLG optimization to avoid an overestimation of the optimal DLG correction factor owing to Mobius3D dose calculation uncertainties. To easily classify small-field VMAT plans from a set of candidate plans, the ratio of the dose change to the change in the DLG correction factor can be calculated as an alternative method to estimate the average MLC opening size.
- Especially when the DLG optimization is performed for multiple machines, developing a set of reference plans representing site-specific patient population is desirable according to the recommendations of the AAPM Task Group 119 report [13].
- For Elekta linear accelerators (Synergy and VersaHD with Agility MLC), a resulting DLG correction factor is expected to be within a range of 0.0 to 0.5. Users of the same model linear accelerators may refer to these DLG correction factor values after conducting their own DLG optimization.
- Under the existence of MobiusFX dose calculation uncertainties, phantom-based measurements need to be performed when MobiusFX-based verification fails.
- Accurate calibration of the machine output is prerequisite for the Mobius3D commissioning and should be periodically performed.

A limitation of this study is that commissioning of Mobius3D and clinical implementation of MobiusFX were performed only for one energy (6 MV X-ray with flattening filter) and linacs of one specific vendor (Elekta) although the results were presented for multiple Elekta linacs. At the authors’ institute, MobiusFX was not yet used for stereotactic radiosurgery and stereotactic body radiation therapy plans (therefore, for flattening filter-free X-ray energies), which are involved with beam radiations passing through small collimating apertures; Mobius3D dose calculation uncertainties for small fields have been reported. Future studies can be conducted to evaluate the Mobius3D dose calculation accuracy and the feasibility of using the proposed commissioning methodology for other X-ray energies and for linacs of other vendors.

5. Conclusions

The vendor-provided reference and measured values for PDD, OAR, and OF were in agreement, except for the OAR at relatively large off-axis distances (7.5, 10, 15, and 20 cm). The machine-to-machine variation was also smaller than 2% for all of the beam data except the OAR at relatively large off-axis distances (10, 15, and 20 cm). It was demonstrated that the DLG optimization including small-field VMAT plans resulted in overestimated DLG correction factors. Due to dose calculation uncertainties, MobiusFX-based VMAT verifications resulted in some false-positively failure cases, which passed the phantom-based verification.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

