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Beyond Open-Field QA: Daily DMLC Monitoring

Fatih Biltekin[1]

fatih.biltekin@hacettepe.edu.tr

Hacettepe University

Gokhan Ozyigit[1]

Hacettepe University

Ferah Yildiz[1]

Hacettepe University

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Abstract

Routine linear accelerator quality assurance (QA) primarily characterizes beam constancy under simple irradiation conditions, whereas dynamic multileaf collimator (DMLC) performance is generally assessed with dedicated periodic tests. This study evaluated the long-term clinical implementation and additional information provided by a daily 6 MV flattening-filter-free (6FFF) DMLC QA field used together with an energy-matched 6FFF open-field measurement. Routine morning QA data acquired from May 2024 to August 2026 on two Elekta Versa HD linear accelerators were retrospectively evaluated using two independent electronic portal imaging device (EPID)-based dosimetry workflows: EPIbeam (DOSIsoft) for pretreatment verification and iViewDose for in vivo dose reconstruction. Each workflow was analyzed separately using its institutional Pass, Alert, and Action levels. The analysis included 548 EPIbeam QA sessions and 490 iViewDose QA sessions containing both 6FFF open-field and DMLC measurements. When the open-field result was Pass, the DMLC result reached Alert or Action in 35/531 EPIbeam sessions (6.6%; 95% CI, 4.8-9.0%) and 85/489 iViewDose sessions (17.4%; 95% CI, 14.3–21.0%); the reverse discordance occurred only once in each workflow (both $p < 0.001$). Mean gamma and the upper 1% gamma value provided additional longitudinal information beyond the gamma passing rate (GPR). In routine clinical use, the complete morning QA workflow was generally completed in < 5 min with EPIbeam and < 10 min with iViewDose. Daily DMLC monitoring therefore provided a practical additional assessment of dynamic delivery constancy within routine EPID-based linac QA.

1 Introduction

Modern linear accelerator quality assurance (QA) includes periodic assessment of beam output, beam profiles, mechanical performance, and multileaf collimator (MLC) positioning accuracy. The increasing clinical use of intensity-modulated radiation therapy (IMRT) and volumetric-modulated arc therapy (VMAT) has increased the importance of verifying dynamic delivery performance in addition to conventional static-field constancy. In these techniques, delivered fluence depends on coordinated MLC motion, monitor-unit delivery, dose rate, and, for rotational treatments, gantry motion. A simple open field remains valuable for daily beam constancy, but it does not reproduce the modulation and temporal characteristics of a dynamically delivered treatment field.

AAPM Task Group 142 and Task Group 198 provide the general framework and implementation guidance for linear accelerator QA [1, 2]. More recently, AAPM Medical Physics Practice Guideline 8.b emphasized that performance tests should reflect the clinical use of the treatment unit and recommended quantitative MLC leaf-position testing weekly and a sliding-window or VMAT holistic test monthly for clinics using these techniques [3]. The guideline also notes that the relationship between machine MLC QA and patient-specific QA is evolving and that more rigorous MLC testing may be required in contemporary practice. These recommendations do not imply that dynamic MLC testing must be performed daily, but they provide a rationale for investigating whether a short dynamic measurement can add useful information to a daily QA program without replacing established weekly or monthly tests.

EPIDs are well suited to this purpose because they are integrated into the treatment unit, provide high spatial resolution, and allow rapid digital acquisition without additional detector positioning. EPID dosimetry has been used for beam constancy, MLC verification, pretreatment verification, and in vivo dosimetry [4–6]. AAPM Task Group 330 recently summarized the use of EPIDs for linac QA and highlighted both their efficiency and the need to understand detector-specific response characteristics when they are used as dosimeters [4]. These features allow a routine daily QA program to combine a simple beam-constancy measurement with a reproducible dynamic field using the same onboard detector.

Previous studies have shown that dynamic MLC QA can be performed efficiently with EPID-based methods. Richart et al. described a daily EPID-based dynamic IMRT QA program incorporating a garden-fence test, a sweeping-slit test, and a leaf-speed test, with the complete procedure taking less than five minutes [7]. Meyers et al. subsequently evaluated daily Elekta Agility MLC positional data over 11–37 months and demonstrated the value of longitudinal monitoring and statistical process control for identifying servicing effects, beam-related variations, and imaging artifacts [8]. Other investigations have shown that EPID-based methods can quantify MLC position, gap width, leaf speed, and dynamic delivery with high sensitivity [9, 10]. Most of these approaches use dedicated geometric or sliding-gap patterns. Less information is available on the long-term clinical use of a single standardized DMLC QA field incorporated directly into routine daily machine QA and interpreted together with an open-field measurement at the same photon energy.

A practical way to assess the additional information provided by such a DMLC measurement is to compare it with a low-complexity field delivered with the same energy. In the present QA approach, a 6FFF open field provides a reference for the combined stability of the photon beam and EPID measurement chain, whereas the 6FFF DMLC field adds dynamic leaf motion, MLC-defined dose gradients, and a spatially modulated fluence pattern. Agreement for both fields can be characterized using the gamma method, which combines dose difference (DD) and distance-to-agreement (DTA) criteria [11, 12]. The gamma passing rate (GPR) provides a convenient overall summary, while mean gamma and the upper 1% gamma value (γ1%) retain additional information on the distribution of gamma values. This is particularly relevant in longitudinal QA when GPR remains concentrated near the upper end of its scale and smaller changes may be more apparent in distribution-based gamma metrics [13, 14].

Because EPID dosimetry can be implemented using different reconstruction approaches, the reproducibility of the daily DMLC concept should also be interpreted within the characteristics of each system. Pretreatment portal dosimetry and in vivo EPID dose reconstruction differ in acquisition geometry, dose-reconstruction methodology, calibration, and clinical acceptance levels [5, 15, 16]. Their absolute gamma values should therefore not be considered interchangeable. However, observing the same direction of open-field/DMLC discordance in two independent EPID workflows would support the general clinical value of the approach rather than a finding specific to one analysis platform.

In our routine morning QA program, 6 MV open-field, 6FFF open-field, and 6FFF DMLC measurements were performed before clinical treatment. Because daily DMLC follow-up was performed with the 6FFF beam, the present study focused on the energy-matched 6FFF open-field and DMLC measurements. The primary aim was to determine whether daily DMLC monitoring identified additional Alert- or Action-level findings when the corresponding 6FFF open-field result remained within the institutional Pass range. Secondary aims were to characterize the longitudinal behavior of GPR, mean gamma, and γ1% and to evaluate relevant temporal patterns observed during routine clinical use. The study was designed to assess daily DMLC monitoring as a complementary component of a broader linac QA program rather than as a substitute for established output, beam-profile, quantitative MLC, or end-to-end verification procedures.

2 Materials and methods

2.1 Study Design

This retrospective longitudinal study evaluated routine morning machine-QA measurements acquired from May 2024 through August 2026 on two Elekta Versa HD linear accelerators. Within each treatment unit, analysis was restricted to QA sessions in which both the 6FFF open-field and 6FFF DMLC measurements were available.

The study was designed to evaluate the additional information provided by daily DMLC monitoring beyond an energy-matched open field. The DMLC measurement was considered an additional component of routine machine QA and not a replacement for established output, beam-profile, quantitative MLC, or periodic end-to-end QA procedures.

2.2 CT Simulation and Treatment Planning

A 30 × 30 × 10 cm³ RW3 solid-water phantom (PTW Freiburg GmbH, Freiburg, Germany) was used to establish a reproducible reference geometry. CT simulation was performed using a GE BrightSpeed CT simulator (GE HealthCare, Waukesha, WI, USA) at 100 kVp and 250 mAs, with a reconstructed slice thickness of 2.5 mm. The CT dataset was transferred to the RayStation treatment planning system version 8B (RaySearch Laboratories AB, Stockholm, Sweden) for treatment planning.

The phantom was positioned at a source-to-surface distance of 95 cm, corresponding to a reference depth of 5 cm on the central axis. Three routine QA plans were prepared on the same planning dataset: a 6 MV 10 × 10 cm² open field, a 6FFF 10 × 10 cm² open field, and a single-field 6FFF DMLC plan. The present study included the latter two plans. The DMLC plan was generated by inverse optimization to produce a square modulated dose distribution containing a smaller central lower-dose square region, creating repeated dynamic leaf motion and multiple MLC-defined dose gradients while retaining a simple geometry suitable for reproducible daily delivery (Fig. 1).

2.3 Treatment Units and Daily QA

Measurements were performed on two Elekta Versa HD linear accelerators (Elekta AB, Stockholm, Sweden), each equipped with an Agility MLC and an iViewGT EPID. The treatment units had been clinically configured with matched photon-beam characteristics.

The institutional morning QA program included 6 MV open-field, 6FFF open-field, and 6FFF DMLC measurements. Because daily DMLC follow-up was performed with the 6FFF beam, only the 6FFF open-field and 6FFF DMLC measurements were included in the present analysis.

On the first treatment unit, EPID dosimetry was performed using EPIbeam (DOSIsoft SA, Cachan, France) for pretreatment portal-dose verification. On the second treatment unit, measurements were evaluated using iViewDose version 1.0.1 (Elekta AB, Stockholm, Sweden), an in vivo EPID dose-reconstruction system used in the routine machine-QA workflow. The two EPID workflows were analyzed separately because their dose-reconstruction methods and institutional acceptance levels differed.

The 6FFF open-field and DMLC measurements were delivered sequentially during morning QA and generally constituted the first irradiations of the treatment day. Independent ionization-chamber output constancy was measured approximately weekly and remained generally within ± 0.5% of the institutional baseline; these measurements were used as supporting information because they were not simultaneous with every EPID acquisition.

2.4 EPID Dosimetry and Data Analysis

Both EPID workflows provided the same three gamma descriptors used in this study: GPR, mean gamma, and the upper 1% gamma value (γ1%). GPR was defined as the percentage of evaluated points with γ ≤ 1. The EPIbeam parameter reported as “gamma max (1%)” and the iViewDose parameter reported as “gamma 1%” were treated as the corresponding γ1% measure for longitudinal analysis.

Gamma analysis was performed using 3% DD/3 mm DTA criteria within the respective clinical workflows. EPIbeam used the pretreatment portal-dose comparison, whereas iViewDose derived the same reported gamma descriptors from its three-dimensional in vivo dose-reconstruction workflow. Because the two systems differ in dose reconstruction and acceptance levels, absolute gamma values were analyzed within each workflow and were not pooled or directly compared between systems.

For the historical iViewDose dataset, GPR was available for all included QA sessions. Mean gamma and γ1% were obtained from the archived analysis screens. A small subset of screenshots did not contain a legible numerical value for one of these continuous parameters; these observations were treated as missing and no values were imputed.

For EPIbeam, GPR ≥ 95% was classified as Pass, 90% to < 95% as Alert, and < 90% as Action. For iViewDose, GPR ≥ 85% was classified as Pass, 80% to < 85% as Alert, and < 80% as Action. The Pass limits reflected the corresponding institutional workflows; the three-state classification was used to distinguish results within the Pass range, a review range, and an Action-level range during longitudinal analysis.

The primary endpoint was a QA session in which the 6FFF open-field result was Pass while the DMLC result was Alert or Action. The additional DMLC detection proportion was calculated as the number of these sessions divided by the number of sessions with an open-field Pass. A second endpoint evaluated Action-level discordance. Longitudinal GPR, mean gamma, and γ1% were secondary metrics.

Categorical variables were summarized as counts and percentages. Continuous variables were reported as mean ± standard deviation (SD). Because the primary endpoint consisted of two paired discordant outcomes within the same QA session, the exact McNemar test was used to compare the two discordant directions: open-field Pass/DMLC Alert-Action versus open-field Alert-Action/DMLC Pass. A separate exact McNemar test was applied to Action-level discordance. The additional DMLC detection proportion was reported with a 95% Wilson confidence interval. Same-session associations between open-field and DMLC mean gamma and γ1% were assessed with Spearman rank correlation.

During review of the EPIbeam longitudinal results, a temporal clustering of Alert/Action measurements was noted during the earlier study period, particularly on some Monday mornings. Clinical review identified unstable treatment-room conditions during seasonal transitions, with observed room temperatures of approximately 15–18°C on some weekends. After modification of the room-control strategy, daily temperature and pressure monitoring was introduced and room temperature was maintained approximately within 20–23°C. An exploratory analysis compared event proportions before and after June 1, 2025 and Monday versus other weekday measurements using Fisher's exact test. Because complete pre-intervention temperature records were not available, this analysis was interpreted as an association with room-condition stabilization rather than a direct temperature-response analysis. All tests were two sided, with $p < 0.05$ considered statistically significant.

3 Results

3.1 Daily DMLC Implementation and QA Classification

Daily DMLC monitoring was maintained throughout the May 2024-August 2026 study period. The analysis included 548 EPIbeam QA sessions and 490 iViewDose QA sessions containing both 6FFF open-field and DMLC measurements. Table 1 summarizes the system-specific Pass, Alert, and Action distributions, and Fig. 2 shows their longitudinal occurrence. In both workflows, the open field remained predominantly within the Pass range, whereas Alert and Action classifications were more frequent for the DMLC measurement.

Table 1
System-specific classification of the 6FFF open-field and DMLC measurements.

EPID system	Field	n	Pass, n (%)	Alert, n (%)	Action, n (%)
EPIbeam	6FFF open field	548	531 (96.9)	4 (0.7)	13 (2.4)
EPIbeam	6FFF DMLC	548	497 (90.7)	20 (3.6)	31 (5.7)
iViewDose	6FFF open field	490	489 (99.8)	0 (0.0)	1 (0.2)
iViewDose	6FFF DMLC	490	405 (82.7)	70 (14.3)	15 (3.1)

3.2 Open-Field/DMLC Discordance

The primary discordance analysis is summarized in Table 2. In EPIbeam, 35 of 531 sessions with an open-field Pass had a DMLC Alert or Action result, corresponding to an additional DMLC detection proportion of 6.6% (95% CI, 4.8-9.0%). The opposite discordance occurred once; the exact McNemar test therefore compared 35 versus 1 discordant sessions and was significant ($p < 0.001$). At the Action level, the corresponding discordant counts were 19 versus 1 ($p < 0.001$).

In iViewDose, 85 of 489 sessions with an open-field Pass had a DMLC Alert or Action result, giving an additional DMLC detection proportion of 17.4% (95% CI, 14.3–21.0%). The opposite discordance occurred once (85 versus 1; $p < 0.001$), while Action-level discordance was 15 versus 1 ($p < 0.001$). These results were interpreted within each EPID workflow and were not used for a direct comparison of software sensitivity.

Table 2
Within-session open-field/DMLC classification matrix.

System	Open-field classification	DMLC Pass	DMLC Alert	DMLC Action
EPIbeam	Pass	496	19	16
EPIbeam	Alert	0	1	3
EPIbeam	Action	1	0	12
iViewDose	Pass	404	70	15
iViewDose	Alert	0	0	0
iViewDose	Action	1	0	0

3.3 Longitudinal Gamma Metrics

The longitudinal mean-gamma and γ1% results are presented in Table 3 and Figs. 3 and 4. EPIbeam GPR remained strongly concentrated near the upper end of the scale, while the continuous gamma metrics showed broader temporal variation. Mean gamma and γ1% showed significant same-session

correlations between the EPIbeam open-field and DMLC measurements (ρ = 0.692 and ρ = 0.695, respectively; both p < 0.001).

For iViewDose, mean gamma was available for 479 open-field and 477 DMLC measurements, with 475 sessions containing both values. γ1% was available for 479 open-field and 461 DMLC measurements, with 458 sessions containing both values. Mean gamma showed no significant same-session correlation between the two fields (ρ = 0.032, p = 0.490), whereas γ1% showed an inverse association (ρ=-0.506, p < 0.001). Figure 4B also shows a temporary divergence of the two iViewDose γ1% series from approximately March through May 2026; this was not accompanied by a parallel deterioration in GPR or mean gamma.

Table 3
Longitudinal gamma-distribution metrics. Values are mean ± SD. *p < 0.001. No missing iViewDose values were imputed.

System	Metric	Valid n (open/DMLC)	6FFF open field Mean ± SD	6FFF DMLC Mean ± SD	Paired n; Spearman ρ
EPIbeam	Mean gamma	548 / 548	0.405 ± 0.103	0.405 ± 0.109	548; 0.692*
EPIbeam	γ1%	548 / 548	0.756 ± 0.171	1.008 ± 0.176	548; 0.695*
iViewDose	Mean gamma	479 / 477	0.411 ± 0.051	0.568 ± 0.067	475; 0.032
iViewDose	γ1%	479 / 461	1.961 ± 0.091	2.043 ± 0.052	458; -0.506*

3.4 Temporal Pattern in EPIbeam Results

A distinct concentration of EPIbeam Alert/Action results was observed during the earlier part of the study, particularly in some Monday morning measurements. Clinical review identified unstable treatment-room conditions during seasonal transitions, with observed temperatures of approximately 15–18°C before the intervention and subsequent stabilization at approximately 20–23°C. As summarized in Table 4, Alert/Action results decreased after room-condition stabilization, with a more pronounced reduction for the DMLC measurement (44/260 [16.9%] to 7/288 [2.4%], p < 0.001) than for the open field (12/260 [4.6%] to 5/288 [1.7%], p = 0.081).

The change was also evident in Monday measurements: DMLC Alert/Action results decreased from 18/50 (36.0%) before stabilization to 1/60 (1.7%) afterward (p < 0.001), while open-field Alert/Action results decreased from 8/50 (16.0%) to 0/60 (0.0%) (p = 0.001). These findings were treated as an exploratory temporal association because complete quantitative temperature records were not available throughout the earlier period.

Table 4
Exploratory EPIbeam temporal analysis before and after stabilization of treatment-room conditions.

Period	n	Open Alert/Action, n (%)	DMLC Alert/Action, n (%)
Before room-condition stabilization	260	12 (4.6)	44 (16.9)
After room-condition stabilization	288	5 (1.7)	7 (2.4)
Monday before stabilization	50	8 (16.0)	18 (36.0)
Monday after stabilization	60	0 (0.0)	1 (1.7)

4 Discussion

The main finding of this study is that a standardized DMLC measurement performed as part of routine morning QA provided additional information beyond an energy-matched 6FFF open-field measurement over more than two years of clinical use. This result was reproduced in two independent EPID dosimetry workflows. In the EPIbeam workflow, 6.6% of sessions with a passing open-field result had a DMLC result in the Alert or Action range, whereas the corresponding proportion was 17.4% in iViewDose. The reverse pattern, in which the open field was non-Pass while the DMLC result remained Pass, occurred only once in each workflow. Because the two systems use different dose-reconstruction approaches and different institutional thresholds, the two percentages should not be interpreted as a comparison of software sensitivity. The important observation is the consistency of the within-system result: a dynamically modulated field generated additional QA findings that were not evident from the corresponding open field.

The feasibility of daily dynamic MLC QA has been demonstrated previously. Richart et al. reported a daily EPID-based program using several dedicated dynamic MLC patterns and showed that leaf-position, gap-width, and leaf-speed changes could be detected within a clinically practical procedure [7]. The present work differs in purpose and implementation. Rather than combining several geometric tests, we used one fixed DMLC dose pattern designed for repeated routine delivery and evaluated it together with a simple energy-matched open field. This approach does not provide the component-level diagnostic detail of a picket-fence or sweeping-slit analysis, but it is straightforward to integrate into morning QA and can be followed longitudinally as a stable reference measurement. The long observation period and the large number of routine measurements are relevant because a test intended for daily use should be judged not only by its sensitivity but also by its reproducibility and ease of integration into clinical workflow.

The longitudinal results also show that repeated QA measurements contain information beyond isolated tolerance checks. Meyers et al. analyzed daily Elekta Agility MLC position data across 13 linacs and showed that control-chart behavior could identify special-cause events associated with servicing, beam-spot motion, and image artifacts even when overall MLC performance remained highly stable [8]. Our study did not use formal statistical process-control limits as the primary method, but the same general principle is evident in the gamma results. In EPIbeam, open-field GPR was strongly concentrated near

100%, whereas mean gamma and γ1% continued to vary over time. Thus, a stable or very high GPR did not imply that all information contained in the gamma distribution was unchanged.

This observation should not be interpreted as a criticism of gamma analysis itself. The gamma method remains a useful and established tool for spatial comparison of calculated and measured dose distributions [11, 12]. The limitation arises when the full gamma distribution is represented only by the percentage of points satisfying $\gamma \leq 1$. Studies in patient-specific QA have shown that GPR may have limited ability to predict clinically relevant dose errors and can be insensitive to certain error patterns [13, 14]. Machine QA is not equivalent to patient-specific QA, and the clinical conclusions of those studies should not be transferred directly. Nevertheless, the same mathematical consideration applies to a repeated machine measurement: two dose distributions may have similar GPR values while differing in the central tendency or upper tail of the gamma distribution. Our results therefore support interpretation of GPR together with mean gamma and γ1% for longitudinal monitoring rather than treating any single metric as sufficient on its own.

The EPIbeam correlations between the open-field and DMLC gamma metrics provide additional context. Mean gamma and γ1% showed Spearman correlation coefficients of approximately 0.69 between the two fields. This indicates that an important portion of day-to-day DMLC variation was shared with the open-field measurement, which is physically reasonable because both fields were delivered with the same energy, treatment unit, EPID, and analysis system within the same morning QA session. Common changes in beam generation, detector response, environmental conditions, or image processing can therefore influence both measurements. For this reason, a DMLC Alert or Action result should not automatically be labeled an MLC failure. The DMLC field should instead be understood as a more complex delivery condition superimposed on the same beam and detector chain. Its added value is that some deviations become more apparent under modulation than in the corresponding open field.

The iViewDose data provided an independent view of the same concept. iViewDose performs in vivo EPID dose reconstruction, whereas EPIbeam was used for pretreatment EPID verification. The two systems therefore differ substantially in methodology, and direct comparison of their absolute GPR, mean gamma, or γ1% values would be inappropriate. Nevertheless, the DMLC field produced more Alert/Action results than the open field in both workflows. This agreement in direction is more informative than the difference between the numerical percentages and suggests that the additional information from the DMLC measurement was not restricted to one software implementation.

The continuous iViewDose metrics require a more field-specific interpretation. Mean gamma was generally higher for the DMLC field than for the open field, but this does not indicate poorer machine performance because the spatial dose distributions are intrinsically different. A notable feature was the temporary divergence of γ1% from approximately March through May 2026, during which the open-field upper 1% gamma value decreased while the DMLC value increased. GPR and mean gamma did not show a parallel deterioration. The upper 1% gamma value is determined by a small subset of the most discrepant points, and those points need not arise from the same spatial region in the two fields. In the

open field they may be dominated by field-edge or off-axis behavior, whereas in the DMLC field they may arise from MLC-defined gradients or the central modulated region. Opposite movement of γ1% can therefore occur without a corresponding global deterioration. Field-specific reconstruction sensitivity or changes in the spatial location of the highest gamma values are also possible contributors. Because the present study did not include direct spatial analysis of the raw gamma maps for this interval, no single mechanism can be assigned. This finding supports interpretation of γ1% together with GPR, mean gamma, and the spatial dose distribution rather than as an isolated indicator.

A distinct temporal clustering of EPIbeam Alert/Action results was observed during the earlier portion of the study, particularly in some Monday morning measurements. Clinical review identified unstable treatment-room conditions during seasonal transitions. The hospital ventilation system and the local split air-conditioning system could occasionally operate in the same cooling or heating direction, and when the treatment room remained closed over the weekend this could produce room temperatures of approximately 15–18°C before the first irradiation. After the problem was identified, the room-control strategy was modified and daily temperature and pressure monitoring was introduced, with room temperature subsequently maintained approximately within 20–23°C. Following this intervention, the frequency of DMLC Alert/Action results decreased from 16.9% to 2.4%, and Monday DMLC Alert/Action results decreased from 36.0% to 1.7%. The open-field results changed in the same direction, although the overall pre/post difference was smaller.

There is a plausible dosimetric basis for this association, but causality should be stated cautiously. Winkler et al. studied an Elekta iViewGT amorphous-silicon EPID and reported a measurable response change during detector warm-up [17]. Renaud and Muir later identified internal detector temperature, power-supply voltage, and accumulated dose among the quantities influencing long-term EPID response after correction for linac output [18]. TG-330 likewise emphasizes that operational and environmental effects should be considered when an EPID is used quantitatively for linac QA [4]. These observations support the plausibility of a temperature-associated first-irradiation effect. However, room temperature is only a surrogate for internal EPID temperature, and complete quantitative temperature records were not available before daily environmental monitoring was introduced. The present data therefore support an association with room-condition stabilization rather than proof of a direct temperature-response relationship.

Independent weekly ionization-chamber output measurements remained generally within approximately ± 0.5% of baseline during the study period. This supports good long-term beam-output constancy and makes a persistent large output drift an unlikely explanation for the overall pattern. Nevertheless, these chamber measurements were not simultaneous with every daily EPID acquisition and therefore cannot establish the beam output at the exact time of an individual EPID deviation. The room-condition finding is best regarded as a clinically relevant observation generated by longitudinal QA and as a basis for prospective investigation.

Several aspects of the study strengthen the interpretation of the results. First, the DMLC measurement was not an experimental test performed for a short validation period; it was maintained within routine morning QA for more than two years. In routine clinical operation, the complete EPIbeam morning QA sequence, including the 6 MV open field, 6FFF open field, and 6FFF DMLC field, was generally completed in less than 5 min. The iViewDose workflow, including phantom placement and the required phantom and output-image acquisitions, was generally completed in less than 10 min. These short workflow times support the practical feasibility of adding a DMLC measurement to daily QA. Second, the DMLC field was interpreted against an energy-matched open field acquired within the same QA session on each treatment unit, providing a simple internal reference for changes common to the beam and detector. Third, the main result was reproduced using two different EPID dosimetry workflows. Finally, the analysis included mean gamma and γ1% in addition to GPR, allowing longitudinal changes to be examined even when the passing rate remained near the upper end of its range.

The daily DMLC measurement should be viewed as complementary to, not a substitute for, established QA. A normal DMLC result does not exclude an energy-specific beam-profile problem, a small individual leaf-position error, or another fault outside the sensitivity of the selected field. Conversely, an abnormal DMLC result does not identify the cause. In our clinical program, the daily measurements are supplemented by weekly and monthly QA that includes independent ionization-chamber dosimetry and more comprehensive EPID-based measurements, beam-shape checks, and periodic end-to-end verification. These procedures address different aspects of machine and workflow performance and provide the additional information required for root-cause investigation when a daily result changes.

The study has several limitations. It was performed at a single institution using two Elekta Versa HD treatment units and one standardized 6FFF DMLC pattern, so the numerical results and institutional thresholds should not be generalized directly to other machines or software. The two EPID systems used different reconstruction approaches and acceptance levels; consequently, their absolute gamma values and the 6.6% and 17.4% additional-detection proportions cannot be interpreted as a head-to-head comparison of system performance. The DMLC measurement is a holistic test and does not localize the source of an abnormality. For iViewDose, the historical archive consisted of stored analysis screenshots rather than a structured numerical export. GPR was available for all included QA sessions, but the numerical mean-gamma or γ1% field was not legible on a small subset of screenshots; metric-specific missingness was below 6%, and no values were imputed. The room-condition analysis was retrospective, and complete temperature records were not available before environmental monitoring was formalized. Serial correlation and seasonal effects may also influence the simple pre/post event comparisons, so these findings should be considered exploratory rather than causal. Weekly ionization-chamber measurements were not simultaneous with daily EPID measurements. Finally, the study did not include deliberate error insertion to determine detection thresholds for specific MLC or beam-delivery faults.

Future work can build on these observations in several directions. The daily room-temperature records now collected prospectively can be linked directly with EPID metrics to test the relationship between environmental conditions and first-irradiation response. Longitudinal in-plane and cross-plane profile

analysis can be quantified rather than followed only visually, and the three-dimensional iViewDose reconstruction can be used to investigate depth-dependent dose-profile behavior over time. Spatial analysis of the measured, reference, difference, or gamma maps may also be extended using radiomic or dosiomic features to determine whether reproducible image-based patterns identify changes that are not captured by GPR, mean gamma, or γ1%. In addition, the availability of EpiGray in the clinic provides an opportunity to establish a further long-term EPID-based dataset on the iViewDose treatment unit and to examine whether the same daily QA findings are reproduced with another independent dosimetry approach. Finally, controlled delivery perturbations could be introduced to determine which specific failure modes are detected by the daily DMLC field and which remain dependent on dedicated periodic QA.

5 Conclusion

Adding a standardized 6FFF DMLC field extended routine daily QA beyond open-field beam constancy to include a direct daily assessment of dynamic delivery behavior. Across two independent EPID-based dosimetry workflows, the DMLC measurement repeatedly identified Alert- or Action-level changes that were not evident from the corresponding 6FFF open-field result, while mean gamma and γ1% provided complementary information when GPR remained close to its upper range. The test was clinically practical, requiring only a few additional minutes within the morning QA workflow. Daily DMLC monitoring therefore offers a simple and reproducible additional layer of linac QA, provided that abnormal findings are interpreted together with conventional output, beam-profile, and dedicated MLC measurements.

Declarations

Competing interests

The authors declare no conflicts of interest.

Ethics approval

Not applicable. This retrospective study analyzed routine linac machine-QA measurements acquired using a solid-water phantom and did not involve human or animal participants or patient data.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

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Author Contribution

F.B. conceived and designed the study, developed the daily DMLC quality assurance protocol, performed the data analysis, interpreted the results, and drafted the manuscript. G.O. and F.Y. contributed to the clinical interpretation of the findings and critically reviewed and revised the manuscript for important intellectual content. All authors read and approved the final version of the manuscript.

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Data Availability

The data analyzed in this study were generated through routine institutional linear accelerator quality assurance procedures. The datasets are not publicly available but may be requested from the corresponding author. Data-sharing requests will be evaluated in accordance with applicable institutional policies and approval requirements.

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Figures

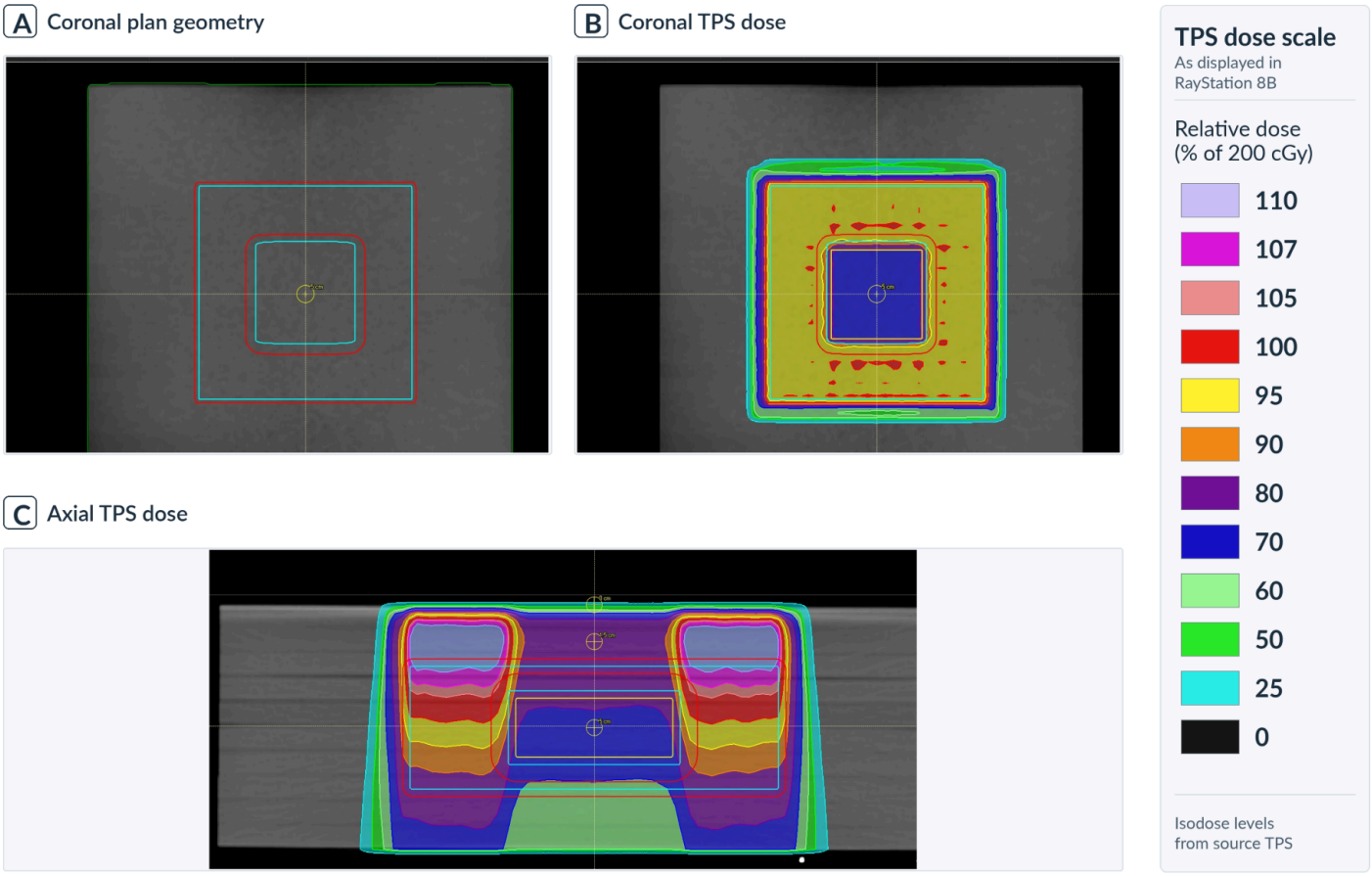


Figure 1

Reference 6 MV flattening-filter-free (6FFF) dynamic multileaf collimator (DMLC) quality-assurance plan calculated in RayStation version 8B on an RW3 solid-water phantom. (A) Coronal planning view showing the outer field and inner modulation-region contours. (B) Corresponding coronal calculated-dose view illustrating the reduced-dose central square and surrounding higher-dose region. (C) Axial calculated-dose view showing the dose distribution through the RW3 phantom. The common color legend reproduces the isodose levels visible in the original treatment-planning-system display, expressed as a percentage of the 200 cGy display reference. These are calculated doses, not EPID measurements.

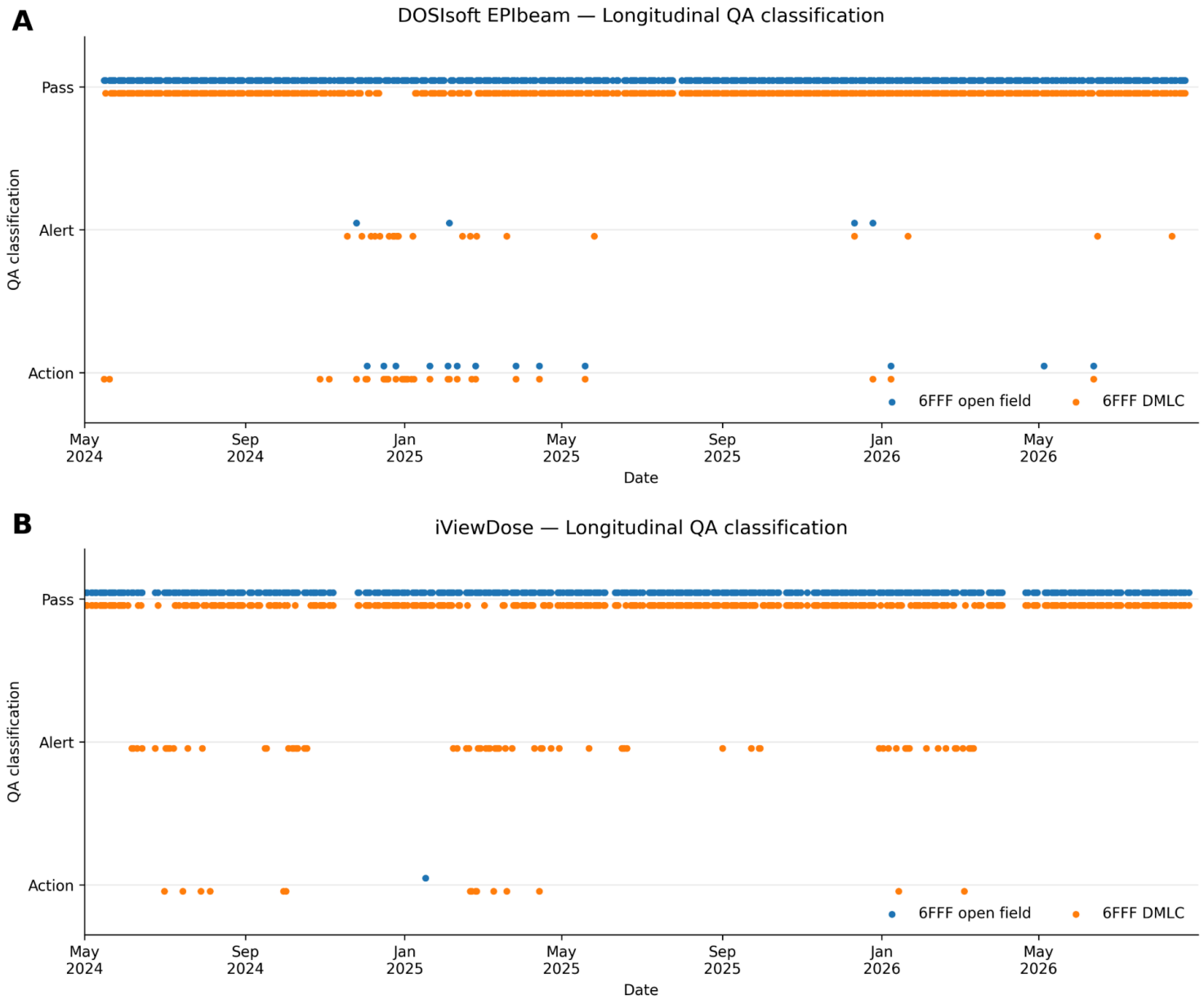


Figure 2

Longitudinal Pass/Alert/Action classification of the 6FFF open-field and DMLC measurements for (A) EPIbeam and (B) iViewDose. Each workflow is interpreted using its own institutional thresholds.

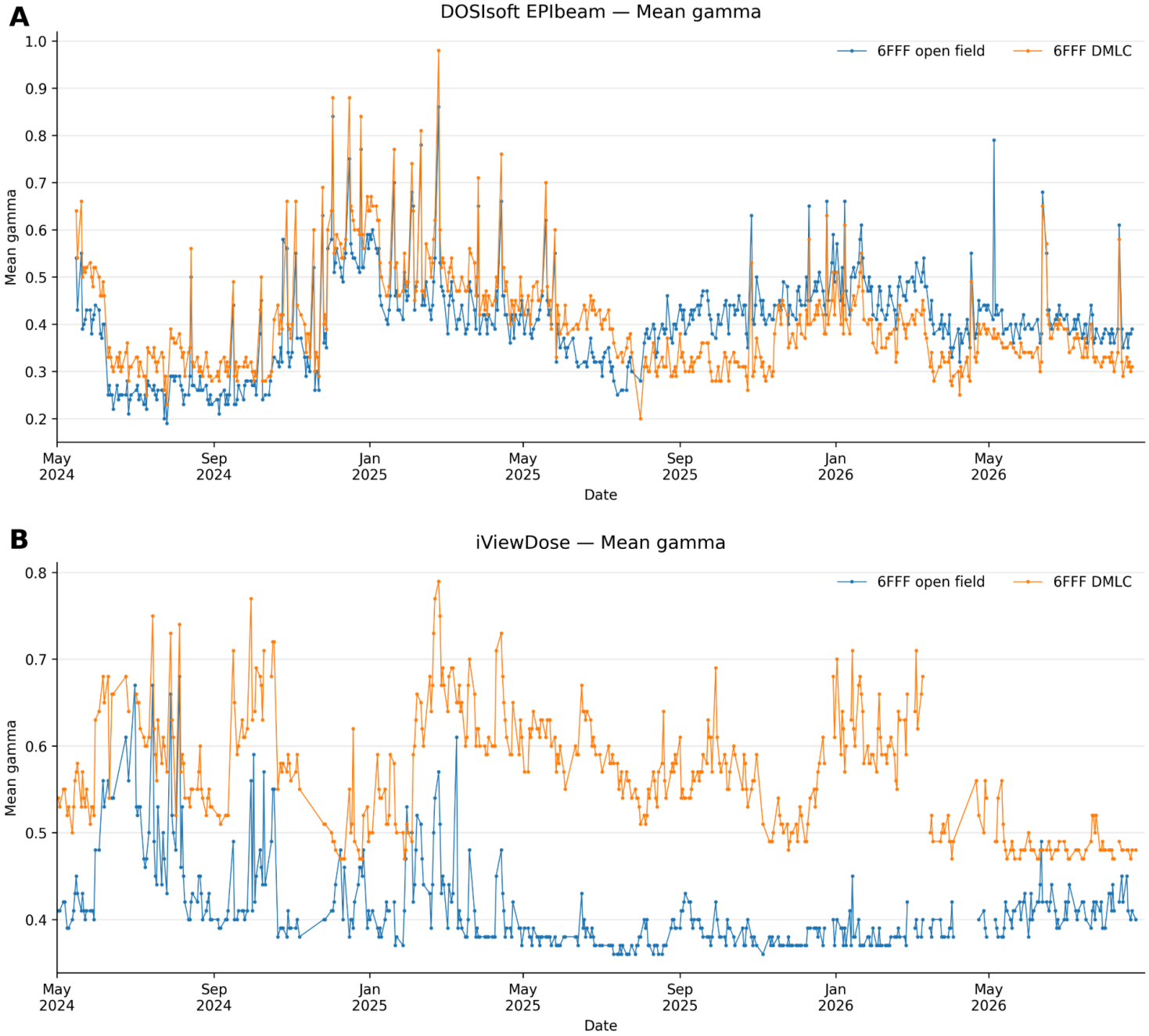


Figure 3

Longitudinal mean gamma for the 6FFF open-field and DMLC measurements in (A) EPIbeam and (B) iViewDose.

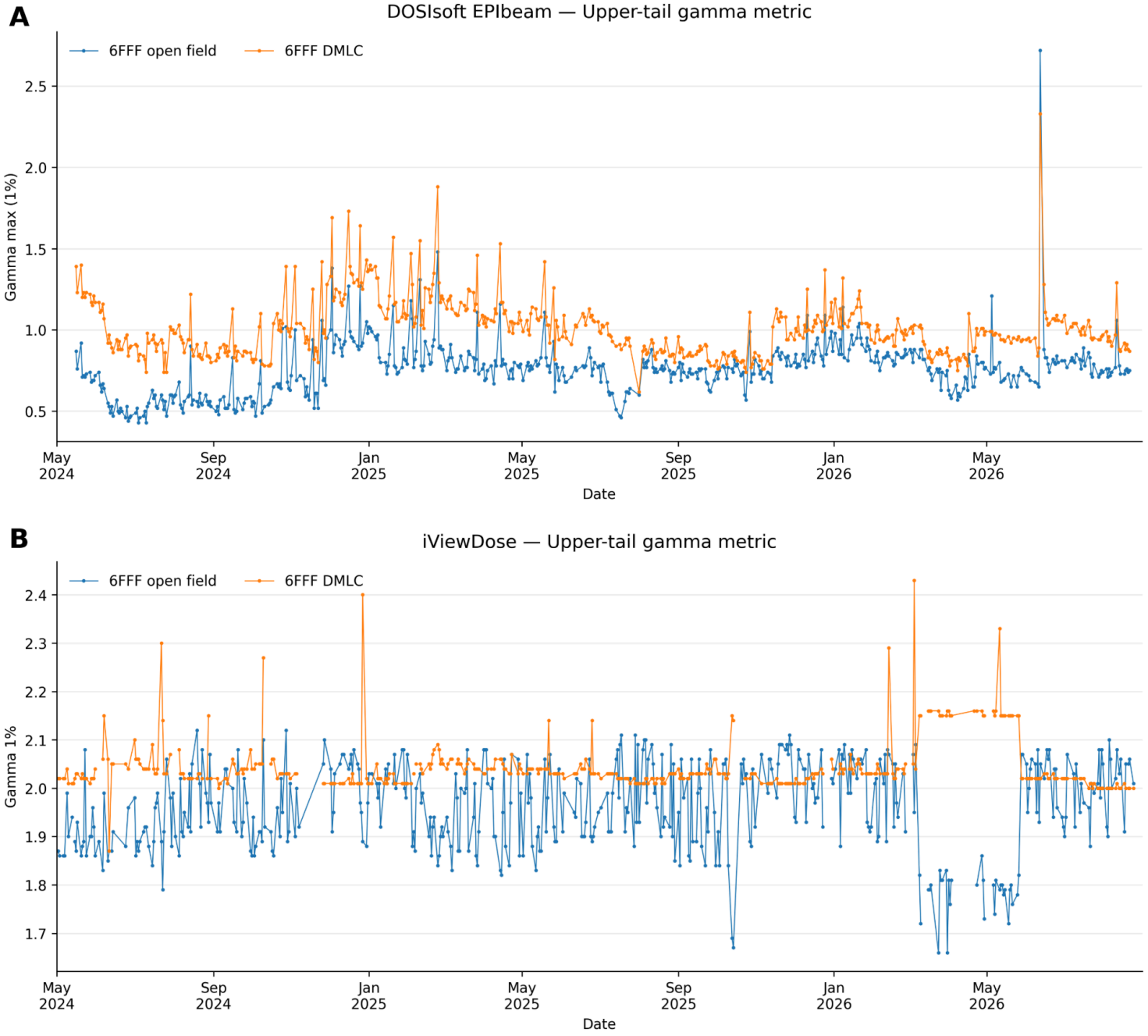


Figure 4

Longitudinal upper 1% gamma value (γ1%) for the 6FFF open-field and DMLC measurements in (A) EPIbeam and (B) iViewDose.