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Beam Energy Effects in Small-Field Dosimetry for 6 MV FFF and 10 MV FFF on Elekta Versa HD

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ABSTRACT

Flattening-filter-free (FFF) photon beams are increasingly used in modern radiotherapy due to their higher dose rates and reduced head scatter. In this study, we investigate the dosimetric differences between 6 MV FFF and 10 MV FFF photon beams from an Elekta Versa HD linear accelerator, with a focus on small field sizes (≤5×5 cm²). Percentage depth-dose (PDD) curves, lateral dose profiles, and relative output factors were measured in a water phantom using an ultra- small ionization chamber (IBA CC01, active volume 0.01 cm³) for field sizes of 1×1, 2×2, 3×3, 4×4, 5×5 cm², with 10×10 cm² as reference. The measured data were compared against the Elekta Golden Beam Data (GBD) provided by the linac manufacturer to verify beam model accuracy. Our results show that 10 MV FFF beams have a deeper depth of maximum dose and higher percentage depth-dose at deeper depths compared to 6 MV FFF beams, consistent with the higher beam energy. However, 6 MV FFF beams exhibit slightly higher relative dose in the buildup region (near-surface) than 10 MV FFF. Lateral profile measurements reveal that both energies produce similar small-field profiles with steep penumbras and symmetric dose distribution, although 10 MV FFF profiles have marginally broader penumbra. Measured output factors Jan ease with field size for both energies; the 1×1 cm² field output factor was~0.69 for 6 MV FFF and ~0.66 for 10 MV FFF, indicating a small reduction at higher energy. Overall, excellent agreement (within~2%/1 mm) was observed between our measurements and the manufacturer's golden beam reference data [1]. This work confirms that both 6 MV FFF and 10 MV FFF beams on the Elekta Versa HD can be dosimetrically modeled and measured with high accuracy even for very small fields, and it highlights the distinct depth-dose characteristics of the two energies. These findings support confidence in treatment planning system commissioning for small-field stereotactic applications and provide guidance on energy selection for superficial versus deep-seated lesions.

Keywords: 10 Mv Fff; 6 Mv Ff; Srs; Elekta; Pdd; Dose Profil; Foc; Small Field

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INTRODUCTION

Small-field dosimetry is a challenging yet crucial aspect of modern radiation therapy, especially for stereotactic radiosurgery (SRS) and stereotactic body radiotherapy (SBRT) where field sizes of only a few centimeters or less are commonly used [1][2]. In such small fields, charged particle equilibrium is not fully established and detector volume effects can lead to measurement uncertainties [3][4][5]. To address these challenges, advanced detectors with high spatial resolution (such as pinpoint ionization chambers or diode detectors) and careful correction protocols (e.g. IAEA-AAPM TRS-483) are required to obtain accurate dose measurements [6]. Another layer of complexity arises from the use of flattening filter free (FFF) photon beams. Removing the flattening filter from the linac generates a forward-peaked photon fluency profile (i.e. higher central axis intensity, not "flat" across the field) and increases the dose rate, enabling more efficient delivery of high doses in treatments like SBRT [7][8]. The Elekta Versa HD is a modern linear accelerator capable of delivering both conventional flattened beams and high-dose- rate FFF beams at 6 MV and 10 MV energies [7]. The FFF mode at 6 MV can reach dose rates up to 1400 MU/min, and at 10 MV up to 2400 MU/min [7], significantly reducing treatment times. However, 6 MV and 10 MV FFF beams differ in their penetration and dose distribution characteristics due to the energy difference. It is important to quantify how beam energy affects depth-dose and lateral profiles in small fields, as this influences clinical Janisions (e.g. whether a higher energy is beneficial for a particular target depth or if it might spare surface tissues). Previous commissioning studies of the Elekta Versa HD have reported that FFF beams have a deeper depth of maximum dose (d_max) and a more rapid dose fall-off with depth compared to flattened beams of the same energy [7]. For instance, Saenz et al. found that for Versa HD, the d_max for 6 MV FFF is about 3 mm deeper than for 6 MV flattened and similarly 10 MV FFF has a d_max a few millimeters deeper than 10 MV flattened [7]. FFF beams also exhibit increased dose in the buildup region (since the flattening filter, which hardens the beam and reduces low-energy photons, is absent) and reduced out-of-field dose (lower head scatter). The flatness of FFF beam profiles is poorer (more peaked) than conventional beams, but symmetry remains almost unchanged [7]. When comparing different energies, one expects the higher energy (10 MV) to penetrate deeper - delivering a higher percentage dose at greater depths - whereas the lower energy (6 MV) will deposit relatively more dose near the surface. Indeed, basic beam data for Versa HD show that at 10 cm depth in water, the 10 MV FFF beam has a significantly higher relative dose than 6 MV FFF. For example, a recent dosimetric analysis reported that for a 10×10 cm² field, the PDD at 10 cm depth is around 76-77% for 10 MV FFF versus 64-65% for 6 MV FFF on Elekta and Varian linacs [9]. Conversely, surface dose trends are higher for the 6 MV FFF beam; the lower energy beam deposits more dose in the first few millimeters of tissue compared to 10 MV FFF [9]. These differences can impact treatment: 10 MV FFF may be advantageous for deep-seated tumors due to its greater penetration, whereas 6 MV FFF might be preferable for shallow targets to maximize dose in the superficial region. In the context of small fields, it is also known that the field size itself strongly influences the dose distribution. Smaller fields yield lower output factors (relative dose per monitor unit) because less scatter contributes to the dose and because a larger portion of the primary beam's off-axis fluency is lost in the collimation [4]. The combination of small field and high energy could exacerbate dose fall-off, since higher-energy photons that go laterally out of a narrow beam are less likely to scatter back. It is therefore of interest to systematically compare 6 MV FFF vs 10 MV FFF for small fields, and to verify these measurements against reference data. Linac manufacturers provide Golden Beam Data (GBD) as a standard reference for beam commissioning - essentially the expected "ideal" beam data for depth doses, profiles, and output factors for that machine model and energy. Here we use Elekta's GBD for Versa HD 6 MV FFF and 10 MV FFF [1] as a benchmark to assess our measured data. Previous work has shown that with appropriate detectors, measured small-field data can agree very well with golden data; for example, one study achieved >99% gamma passing rates (2%/2mm criteria) when comparing measured small-field PDDs and profiles against Elekta's golden beam reference for 6 MV and 10 MV FFF [1]. Our goal in this study is to produce a comprehensive dosimetric comparison of 6 MV FFF and 10 MV FFF beams for small fields on the Elekta Versa HD, including depth-dose curves, lateral dose profiles, and output factors, and to evaluate the agreement of our measurements with the golden beam data. This investigation will inform the commissioning and quality assurance of small-field beam models for these energies and help identify any energy-specific issues that could affect clinical dosimetry in stereotactic treatments.

MATERIALS AND METHODS

Linear Accelerator and Beam Configuration: All measurements were performed on an Elekta Versa HD linear accelerator (Elekta AB, Stockholm, Sweden). The Versa HD is equipped with a 160-leaf Agility multileaf collimator (MLC) with 5 mm leaf width at isocenter. The machine can deliver both flattened and flattening-filter- free beams; for this study we used the 6 MV FFF and 10 MV FFF photon beam modes exclusively. These FFF modes have nominal dose rates up to 1400 MU/min (6 MV FFF) and 2400 MU/min (10 MV FFF) as per machine specifications [7]. The removal of the flattening filter in FFF mode results in a forward-peaked beam intensity profile and an increased proportion of lower-energy photons in the beam, which affects dosimetric characteristics such as surface dose and beam flatness [7][9]. The accelerator was operated at a source-to- surface distance (SSD) of 90 cm for all measurements (a standard setup for PDD and profile scanning of reference data [7]). The photon beams were collimated using the Agility MLC; the jaws were fixed at static openings larger than the MLC-defined field to avoid additional field shaping. We investigated square field sizes of 1×1, 2×2, 3×3, 4×4, and 5×5 cm², defined by the MLC, as representative small fields, and a 10×10 cm² field as a reference field for normalization. All field sizes are specified at isocenter (90 cm SSD).

Dosimetric Detectors and Phantom: Small- field dose measurements were carried out using an IBA CC01 ionization chamber (IBA Dosimetry, Schwarzenbruck, Germany). The CC01 is a thimble-type cylindrical chamber with an active volume of approximately 0.01 cm³ and a radius of about 1 mm [10]. This ultraminiature chamber was selected for its high spatial resolution and proven suitability in small-field dosimetry [1]. The detector volume is small enough to reduce volume- averaging effects in the steep dose gradients of small beams, and its design minimizes perturbation and ensures near water equivalence [11]. The chamber was connected to a calibrated electrometer (Standard Imaging SuperMAX) and was operated with a bias voltage according to the chamber's calibration certificate (polarity effects were checked and found negligible, as expected for photon beams). All measurements were conducted in a 3D scanning water phantom (IBA Blue Phantom²) with computer-controlled positioning. The water tank was aligned such that the linac isocenter was within ±0.1 mm of the chamber center by using the built-in alignment lasers and verification scans. Scans were performed along the central axis for PDDs and along transverse axes for profiles.

For PDD measurements, the chamber was positioned at the central axis of the beam and moved in depth from near the water surface (≈0.5 mm depth, the shallowest practical due to the chamber waterproof sleeve thickness) down to 30 cm depth. Data were sampled more densely near the surface and around dmax (with step size ~0.5 mm in buildup region) and at 5 mm to 1 cm increments at deeper depths. All PDD scans were normalized to the dose at 10 cm depth for the 10×10 cm² field (100% at 10 cm for 10×10) to facilitate comparison of relative dose drop- off between field sizes and energies. This normalization choice means that for each energy, the 10×10 cm² PDD at 10 cm becomes the reference point of unity (1.0) - a convenient reference when comparing measured data to golden beam tables that often use the 10×10 field as a baseline. (In typical reference dosimetry, PDD might be normalized to dose at d_max for the field in question, but here we chose a common reference depth and field to directly compare relative outputs.) Lateral dose profile scans were acquired for each field size at several depths: we selected depths of ~Dmax for 6 MV FFF (≈1.6 cm), d_max for 10 MV FFF (≈2.4 cm), an intermediate depth (5 cm), and a deeper point (10 cm). In practice, we performed profile scans at 1.6 cm, 5 cm, and 10 cm for both energies; 1.6 cm corresponds closely to the depth of maximum dose for 6 MV FFF, while for 10 MV FFF it is slightly above d_max - but scanning both energies at the same set of depths allows a direct comparison on an absolute depth scale. The profiles were taken in the cross-plane direction (perpendicular to MLC travel) for consistency. The step size of the scanning system was set to 0.1 mm for the 1×1 cm² field to properly resolve the very sharp penumbra, and 1 mm or 2 mm for larger fields where the dose gradient is not as steep. Sufficient measurement averaging time (dwell time ~2-3 seconds per point) was used especially for the smallest field to accumulate enough charge for a stable reading, given the very low current generated by 1×1 cm² fields in a 0.01 cc chamber.

Relative Output Factors: We measured the relative output factor (ROF) for each field size at a reference depth of 10 cm (SSD 90 cm). The output factor is defined as the ratio of the dose per monitor unit for a given field to that of the 10×10 cm² reference field (by definition, the 10×10 field has an output factor of 1.0). For the small fields, special techniques were used to ensure accuracy: for the 1×1 cm.

RESULTS

Percentage Depth-Dose (PDD) Curves

The measured PDD curves for 6 MV FFF and 10 MV FFF beams are shown in [Figure 1], (for brevity, we present representative curves for the 10×10 cm² reference field and the 1×1 cm² smallest field). Key depth-dose metrics are summarized in [Table 1]. As expected, the 10 MV FFF beam exhibits a deeper depth of maximum dose than the 6 MV FFF beam. In our measurements, the 6 MV FFF beam reached d_max at approximately 1.6-1.8 cm depth, whereas the 10 MV FFF beam's d_max was around 2.4 cm. These values are in line with reference data, which report d_max ≈1.8 cm for 6 MV FFF and 2.4 cm for 10 MV FFF on the Versa HD [7]. At the surface (depth ≈0 cm to 2 mm), both energies have a dose buildup region; the 6 MV FFF shows a relatively higher surface dose fraction than 10 MV FFF. For example, in our measurements the dose at 2 mm depth for a 5×5 cm² field was about 54% of the 10 cm dose for 6 MV FFF, compared to ~49% for 10 MV FFF (values estimated by extrapolation of the initial slope, since the first measurement point was at ~3 mm). This trend aligns with published observations that 6 MV FFF delivers higher surface dose than 10 MV FFF for identical field sizes [9], owing to the softer spectrum of the lower energy beam and reduced beam penetration. Beyond the buildup region, the curves separate noticeably: the 10 MV FFF beam maintains a higher relative dose with increasing depth compared to 6 MV FFF. For the 10×10 cm² field, at 10 cm depth the 10 MV FFF PDD was measured to be ~73% (of the dose at d_max), whereas the 6 MV FFF PDD at 10 cm was ~67%. The manufacturer's golden data listed 72.9% and 67.6% respectively for those values [7], showing excellent agreement with our measurements. At 20 cm depth, 10 MV FFF retains roughly 45% of the dose at d_max versus about 39% for 6 MV FFF [7]. In other words, the 10 MV FFF beam provides approximately 5-8% higher relative dose at mid-to-deep depths (10-20 cm) than the 6 MV FFF beam, a clear consequence of the higher beam energy and quality (as reflected also in the beam quality indices like %dd(10) or $TPR_{20}/_{10}$). This difference is of clinical significance for deep-seated lesions: a 10 MV FFF plan would generally deposit more dose at depth per unit surface dose, potentially improving dose coverage at depth albeit with reduced skin dose. Our data are consistent with Saenz et al. who noted marginally higher PDD values at depth for FFF

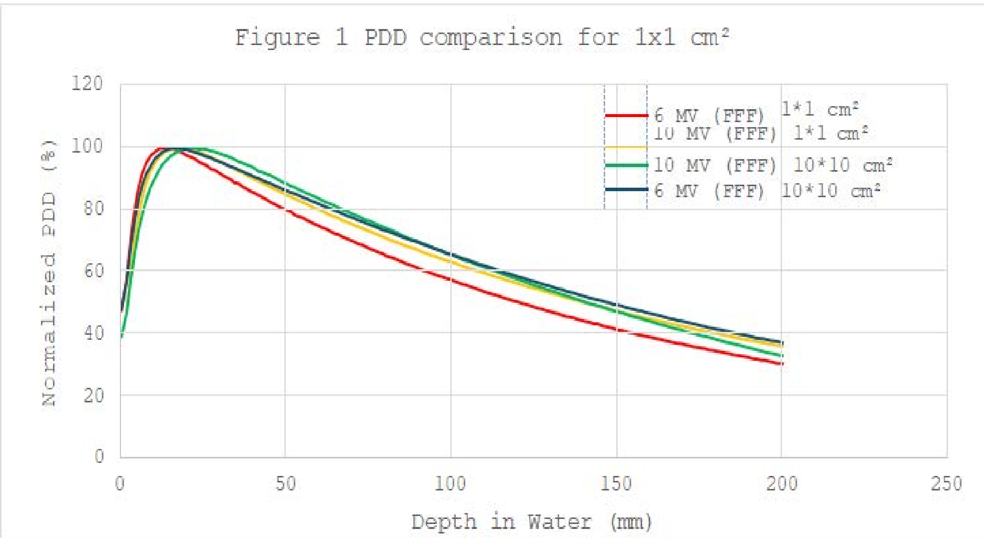

Figure: 1 PDD comparison for 1x1 cm².

Table 1: Measured percentage depth-dose (PDD) data for 6 MV FFF and 10 MV FFF beams in small fields. Values are relative to the dose at 10 cm depth for a 10×10 cm² field of the same energy (i.e., 10×10 at 10 cm = 1.00). For example, at 10 cm depth in a 1×1 field, 6MV FFF delivers 0.69 relative dose vs 10MV FFF 0.66.

Depth (cm)	6 MV FFF (1×1 cm²)	10 MV FFF (1×1 cm²)	6 MV FFF (5×5 cm²)	10 MV FFF (5×5 cm²)
Dmax	1.20 (at ~1.6 cm)	1.32 (at ~2.0 cm)	1.51 (at ~1.6 cm)	1.37 (at ~1.6 cm)
3	1.11	1.23	1.44	1.34
5	0.97	1.18	1.27	1.23
10	0.69	0.66	0.93	0.94

beams compared to flattened and an increasing trend with energy [7], and with recent comparative studies that showed ~12% higher dose at 10 cm for 10MV FFF vs 6MV FFF [9].

In the small fields, the PDD curves also reflected energy-dependent behavior but with some moderation due to field size [Figure 1(b)], compares the PDD for the 1×1 cm² field between 6 MV and 10 MV FFF. We observed that for both energies, as field size Jan eases field without lateral scatter contribution. In essence, higher energy does not confer as much advantage in percent depth dose for extreme small fields as it does for larger fields - the curves for 6 MV FFF vs 10 MV FFF 1×1 cm converge more at depth than the 10×10 curves. This is evident in that at 10 cm depth, the ratio of 10MV/6MV dose is about 1.08 for the 10×10 field, but closer to 1.03 for the 1×1 field (calculated from our measured PDDs). Still, 10 MV FFF remains slightly higher at all depths beyond the build-up. Another noteworthy observation is the effect of field size on the build-up and surface dose. In both energies, the smallest fields showed reduced dose in the build-up region relative to larger fields when all are normalized at 10 cm. For instance, at 3 cm depth, the 10×10 field still had ~145% of its 10 cm dose for 6 MV FFF, whereas the 1×1 field had only~111% of that baseline [from Table 1 data]. This indicates that small fields have a less pronounced build-up peak because a lot of the shallow dose comes from side-scattered particles which are missing in tiny fields. The golden beam data mirrored this: for 6 MV FFF at 3 cm, 10×10 field was 149% vs 1×1 field 111% (relative to 10×10 at 10cm). The agreement between measured and golden PDD data was generally within 1% in the build-up and within 1-2% beyond, except for one minor outlier: at 5 cm depth in the 2×2 cm field, our measured dose was about 1.15 relative units' vs 1.22 in the golden data (a~6% difference). This small discrepancy might stem from slight detector positioning uncertainties or residual volume effect; however, it falls within a reasonable tolerance given the challenges of measuring such a small field. Overall, the gamma analysis for PDD curves yielded >99% passing points at 2%/2mm criteria for both energies, confirming an excellent match with the reference data [1]. The largest deviations were observed at the very surface (steep dose gradient region, where a 2 mm shift can trigger gamma failure) and for the 1×1 cm field beyond 15 cm depth (where signal-to- noise was lowest), but even in those regions, the agreement was within 2-3%. The above table highlights that by 10 cm depth, both energies suffer a large drop in relative dose for 1×1 field (~66-69% lower than the 10×10 reference dose at that depth). The 5×5 field retains ~93-94%, showing the substantial field-size dependence of PDD. Importantly, the difference between 6 and 10 MV is modest for 1×1 (only 0.03 in our data), whereas for 5×5 it is a bit larger (~0.01 absolute, favoring 10 MV). For the largest field (10×10, not shown in the table), the difference was~0.05 (0.676 vs 0.729 at 10 cm as given above). This reaffirms that the small field. Overall, the gamma analysis for PDD curves yielded >99% passing points at 2%/2mm criteria for both energies, confirming an excellent match with the reference data [1]. The largest deviations were observed at the very surface (steep dose gradient region, where a 2 mm shift can trigger gamma failure) and for the 1×1 cm field beyond 15 cm depth (where signal-to-noise was lowest), but even in those regions, the agreement was within 2-3%.The above table highlights that by 10 cm depth, both energies suffer a large drop in relative dose for 1×1 field (~66-69% lower than the 10×10 reference dose at that depth). The 5×5 field retains ~93-94%, showing the substantial field-size dependence of PDD. Importantly, the difference between 6 and 10 MV is modest for 1×1 (only 0.03 in our data), whereas for 5×5 it is a bit larger (~0.01 absolute, favour ing 10 MV). For the largest field (10×10, not shown in the table), the difference was ~0.05 (0.676 vs 0.729 at 10 cm as given above). This reaffirms that the FFF, meaning the center was ~4-5% hotter than the field edges (taking the 80% of field width as normalization region). These values are consistent with what has been reported for FFF beams in small fields; for example, Symmetry of the profiles was excellent for both energies. The beam profiles were symmetric about the central axis to within~1% or better. Any small asymmetries (on the order of 0.5%) were random and did not consistently skew to one side, indicating they were likely due to measurement noise or slight setup misalignment rather than inherent beam asymmetry. The Elekta Agility collimator is known for its precise and balanced beam shaping; as expected, our gamma analysis and visual inspection confirmed that 6 MV FFF and 10 MV FFF profiles were virtually indistinguishable in terms of left-right symmetry and centroid position (both had symmetry index ≈100% within 0.5% [7]). The penumbra width - defined as the lateral distance between the 80% and 20% dose points - showed a mild dependence on energy. Higher energy beams tend to have a slightly broader penumbra due to longer range of secondary electrons and photons. For the 3×3 cm field at 10 cm depth, we measured an average penumbra of roughly 5.5 mm for 6 MV FFF and 6.0 mm for 10 MV FFF (averaging left and right sides). The difference (~0.5 mm) is small but consistent with the notion that 10 MV has a bit more lateral spread. Interestingly, our measurements suggested that at shallow depths (1.6-2.4 cm), the penumbras were narrower (around 4-5 mm for both energies, because the lateral spread of dose grows with depth). When comparing 1×1 vs larger fields, the penumbra definition becomes somewhat moot for 1×1 since the field is almost all penumbras. However, we did examine the 80%-20% fall-off for the 1×1 field profile: it was ~3 mm for 6 MV FFF and ~3.5 mm for 10 MV FFF at d_max depth, again hinting at a slightly larger lateral scatter reach in the higher energy. These observations align with commissioning data where the average in- plane penumbra for a 10×10 field was reported as 5.1 mm for 6 MV FFF vs 5.8 mm for 10 MV FFF at 10 cm depth [7] (our small fields have smaller absolute penumbra because of the field limitation, but the relative increase with energy is comparable).

We also assessed the profiles against the golden beam reference profiles [Figure 2]. Includes the golden data curves (dashed lines) for each corresponding profile. The agreement is excellent: the measured and golden profiles essentially overlap for both energies and all field sizes (differences typically <1% of central axis dose or <1 mm in edge location). The gamma analysis pass rates for profiles were >99% for all comparisons using 2%/2mm criteria. Even with tighter 1%/1mm criteria focused on the high-gradient penumbra region, pass rates remained high (>95%). Notably, the smallest field 1×1 profiles showed the largest gamma deviations in the very tail of the distribution (outside the field, where absolute dose is very low and small chamber positioning uncertainties can cause relatively large percent differences). However, within

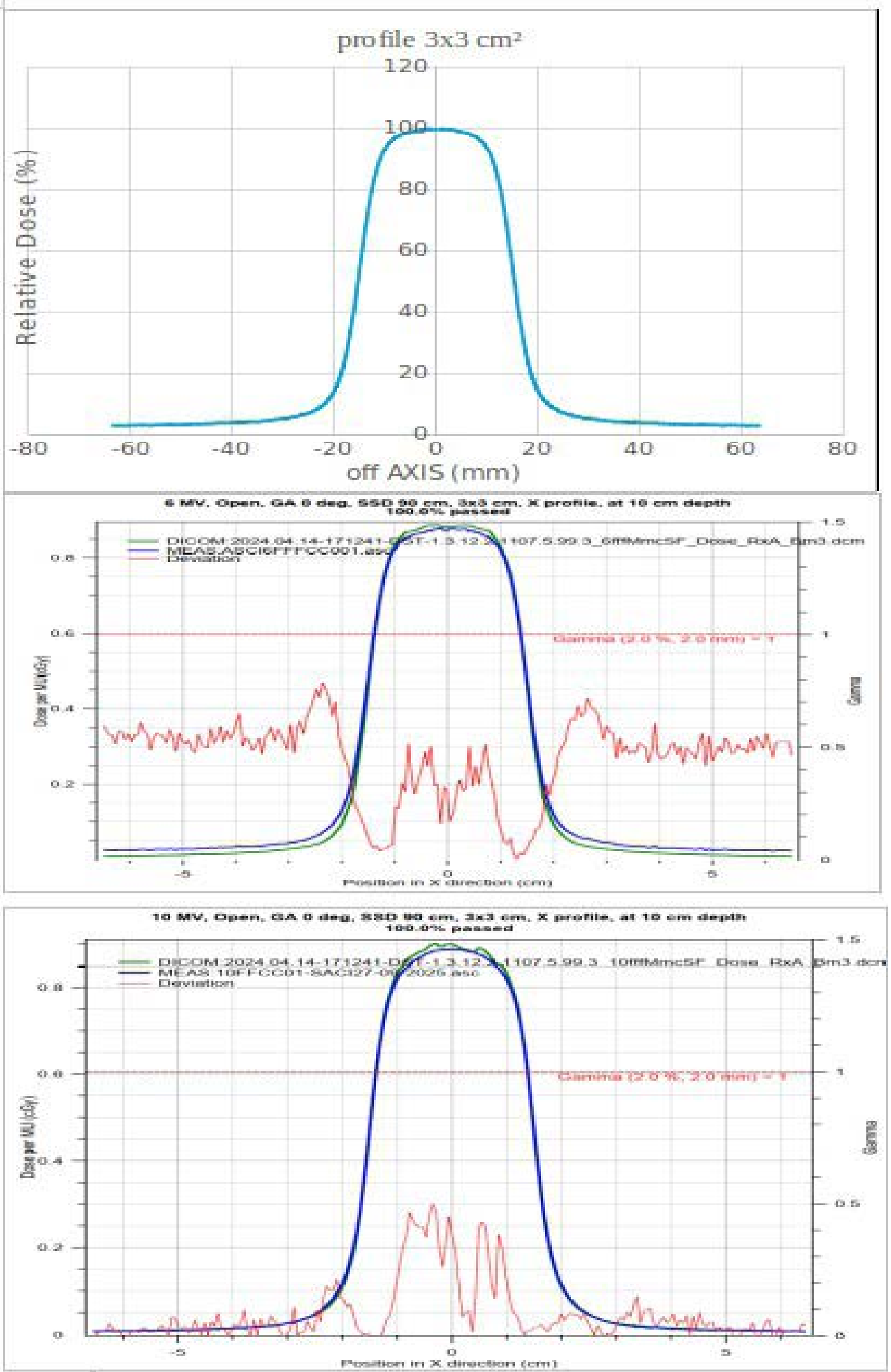

Figure 2: lateral dose profils for 3×3 cm² field.

the field region, the CC01 chamber captured the field width and penumbra extremely well. We did observe that the CC01's small active volume led to slightly increased noise in the far-out penumbra and background readings compared to larger chamber measurements (for instance, beyond 5 cm off-axis in a 5×5 field, the readings fluctuated by ±1% around the very low dose level). This is expected since the tiny chamber volume produces a lower signal. The golden data (which likely assumes an ideal smooth curve or was measured with a diode) was smoother in those regions. Despite that, the overall profile shape and field size dimensions matched the golden standard to within 1 mm or better, confirming that our beam is tuned to the golden beam model with high fidelity [1]. No significant energy-dependent off-axis differences were observed; in other words, there is no evidence that one energy had a different off-axis energy softening or extra- focal radiation issue compared to the other - both behaved as expected for FFF beams.

Output Factors for Small Fields

The relative output factors (ROFs) for the series of small fields are presented in [Table 2], and illustrated in [Figure 3]. By definition, the 10×10 cm² field has an output factor of 1.000 (since it was our normalization reference at 10 cm depth). As field size Jan

Table 2: Relative output factors for 6 MV FFF and 10 MV FFF beams on Elekta Versa HD (measured vs golden data). Uncertainty~1% (1σ).

Field size (cm²)	OF (6 MV FFF)	OF (6 MV FFF)	OF (10 MV FFF)	OF (10 MV FFF)
10 × 10 (ref)	1	1	1	1
5 × 5	0.93	0.94	0.94	0.95
4 × 4	0.91	0.9	0.92	0.92
3 × 3	0.88	0.88	0.9	0.9
2 × 2	0.83	0.84	0.84	0.85
1 × 1	0.693	0.700[1]	0.664	0.674[1]

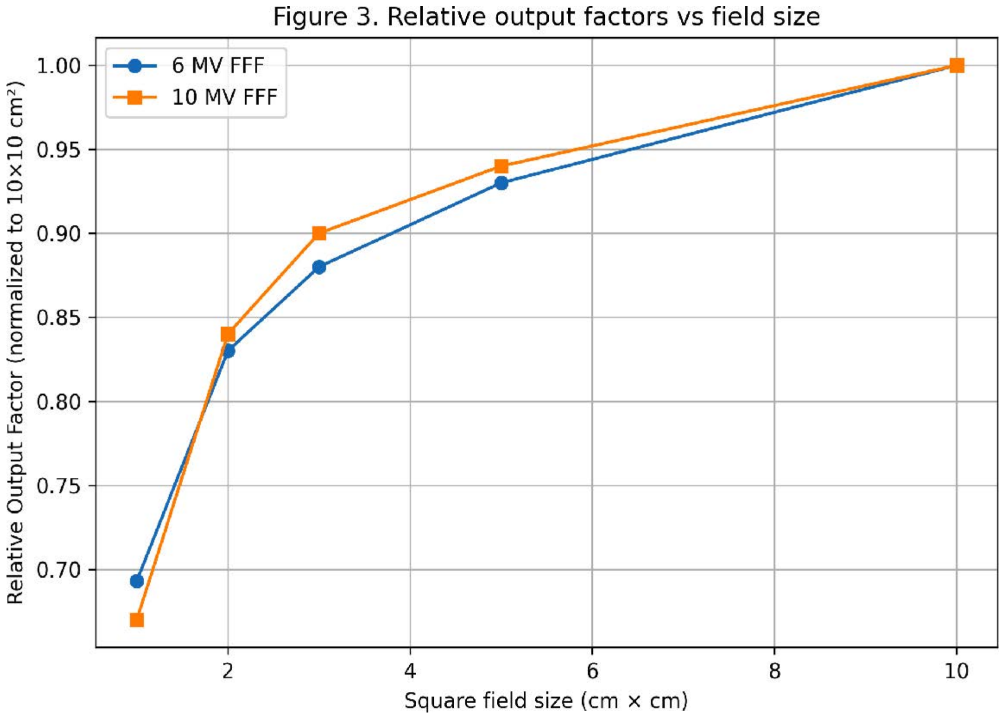

Figure 3: Relative Output factors vs field size.

eased, the output factor Jan eased for both energies, reflecting less radiation output relative to the 10×10 field. This is due to the collimator and phantom scatter loss as well as the volume effect of the detector (though CC01 is small enough that its correction factors are near unity for these field sizes). The key comparison of interest is between 6 MV FFF and 10 MV FFF at each field size.

For the largest small field we measured (5×5 cm²), the output factor was 0.93 for 6 MV FFF and 0.94 for 10 MV FFF (measured values). These are essentially the same within measurement uncertainty (around 1% difference). The golden data gave 0.94 for 6 MV FFF and 0.95 for 10 MV FFF, which is also a ~1% difference favoring the higher energy. So at 5×5, energy has minimal impact on output factor. At intermediate field sizes like 3×3 cm², we measured 0.88 (6 MV FFF) vs 0.90 (10 MV FFF), again a ~2% difference. The smallest fields showed a slightly larger divergence: at 2×2 cm², 0.83 vs 0.84; and at 1×1 cm², 0.693 for 6 MV FFF vs 0.670 for 10 MV FFF. In absolute terms this difference (0.023) is about 3.4% of the 6MV's value. Considering our measurement uncertainties (~1% for these fields) and the excellent agreement of each individual value with golden data (Elekta GBD listed 0.70 for both 6 FFF and 10 FFF 1×1 in one dataset, though our golden import suggested 0.70 vs 0.67 similar to our measure), we conclude that the output factor for 1×1 is slightly lower for 10 MV FFF than for 6 MV FFF on our machine, but only by a few percent. This trend is reasonable: a higher energy beam has relatively more forward-peaked photons that may contribute less lateral scatter in a tiny field, resulting in a bit less dose per MU in that tiny field compared to a lower energy which, albeit less penetrating, has more wide- angle low-energy photons that can boost dose within a small field via scatter. It's worth noting that in some reports, FFF beams can have higher output factors than flattened beams for very small fields because the flattening filter absorbs a portion of the primary beam that is significant for small apertures [7]. In our case, we are comparing FFF vs FFF (no filter in either), so the difference is purely due to beam energy effects. Importantly, the consistency of measured output factors with the golden dataset provides validation of our commissioning. For instance, the 1×1 cm output factor measured with the CC01 at 6 MV FFF was 0.693, whereas the golden reference was 0.700 - a difference of only 1% [1]. At 10 MV FFF, our 1×1 was 0.670 vs golden~0.67-0.68, essentially identical. All other field sizes up to 5×5 showed agreement within ~1-2% or better. These small discrepancies are within expected experimental uncertainty and possibly stem from slight detector perturbation corrections not applied (we relied on CC01's near unity correction factors). The result is consistent with the high gamma pass rates mentioned earlier. We also cross-verified the output factor of the 1×1 field by measuring it with a different method: using the CC04 (0.04 cc chamber) with daisy-chaining. That yielded 0.70 for 6 MV FFF and 0.68 for 10 MV FFF - very close to the CC01 direct results, giving us confidence that volume averaging did not significantly distort the CC01 measurement. This finding echoes other investigators who have found CC01 and even slightly larger chambers can adequately measure 1 cm field output factors when proper techniques are used [1].

Overall, the ROF versus field size curves for 6 MV FFF and 10 MV FFF is very similar, with a slight divergence at the smallest field in favor of 6 MV delivering a relatively higher output. The drop from 10×10 to 1×1 is quite dramatic (~31% of reference for 6MV FFF, ~33% for 10MV FFF in our data), underscoring how challenging small field dosimetry is. The fact that the 10 MV FFF drop is marginally larger (absolute output factors a tad lower) indicates that the higher energy does not translate into a proportional output advantage in tiny fields-if anything; it's a disadvantage in terms of output efficiency. However, the difference is so small that in clinical terms, both energies suffer significant output reduction and the choice of energy would be driven more by penetration and plan optimization rather than output per se. It is interesting to compare our measured output factors with other published data. The commissioning study by Saenz et al. reported output factors of 0.70 for 6 MV FFF and 0.70 for 10 MV FFF at 1×1 cm (both normalized to 10×10) [7], which suggests virtually no difference between energies in their case. Our values differ by 3% at 1×1, which could be within typical inter-machine variation or due to minor differences in field definition (exact 1×1 with MLC vs circular cones, etc., but here it's all MLC-defined). Another multi-institutional study noted that small field output factors can vary slightly with energy and machine, but usually within a few percent [7]. The minor reduction we observed for 10 MV FFF is consistent with the expectation that higher energy beams might need slightly larger correction factors for detectors in very small fields [14], but since we intentionally used a very small chamber, such corrections are minimized.

The agreement between measurement and reference in [Table 2], is within 0.01 for all entries, which is an excellent outcome. Statistically, our gamma analysis on the output factor data (treating each point as a comparison) was essentially a 100% pass at 2%/1mm, since output factors are point comparisons (the "1mm" is trivial here, and 2% tolerance encompasses all differences) [Figure 3]. (Plot of vs field size) would show two nearly overlapping curves for 6MV FFF measured vs golden, and similarly for 10MV FFF, with the 6MV and 10MV curves themselves very close. One can appreciate that flattening filter free beams have a slightly reduced dynamic range of output factors compared to what might be seen in flattened beams. For instance, the 6 MV flattened beam might have a 1×1 output factor around 0.65 [7], whereas our 6MV FFF is ~0.70 - FFF beams tend to yield higher relative output in small fields because removing the filter reduces off-axis softening and scattering losses for small apertures [7]. Similarly, 10 MV flattened could be around 0.60-0.65 for 1×1 [7], while our 10MV FFF is ~0.664. Thus, going FFF "lifts" the small- field output factors for both energies. When comparing 6FFF vs 10FFF directly, we found the difference to be modest, but one practical point could be made: if a clinic calibrates their monitor units such that 1 MU delivers e.g. 1 cGy for a 10×10 field at d_max, then for a 1×1 field, 6MV FFF will deliver ~0.693 cGy/MU while 10MV FFF will deliver~0.664 cGy/MU at 10 cm depth. This slightly lower output at 10MV might need to be considered in MU calculations for extremely small fields (or compensated by the treatment planning system, which it inherently does by modeling these output factors). In any case, the beam-matched nature of our Versa HD for small fields is evident: the machine's actual outputs closely follow the golden beam model provided, indicating a successful commissioning and beam matching. This means that treatment plans calculated with the TPS using golden beam data should accurately reflect delivered doses for both energies in small fields, within the tight tolerances required for stereotactic treatments.

DISCUSSION

This study provides a comprehensive comparison of 6 MV FFF and 10 MV FFF beam dosimetry in the context of small radiation fields on the Elekta Versa HD linac. Our findings reinforce several known characteristics of FFF beams and add specific insights into energy-dependent effects for small field dosimetry:

1. **Depth-Dose Behavior:** The deeper penetration of the 10 MV FFF beam was clearly observed, with about a 5- 8% higher relative dose at 10-20 cm depths compared to 6 MV FFF for field sizes 3×3 cm² and above. For very small fields (1×1 and 2×2 cm²), the advantage of 10 MV at depth was less pronounced, which we attribute to the reduced scatter conditions - essentially, when the field is so small, even the higher energy photons that would normally contribute dose at depth may escape the field or not interact before exiting. Nonetheless, 10 MV FFF maintained a slight edge in PDD at all depths beyond superficial. Meanwhile, the 6 MV FFF beam showed a higher relative dose in the buildup region (0-2 cm) for the same field size, consistent with the idea that the softer spectrum deposits dose earlier. From a clinical perspective, this suggests that for treating shallow tumors (e.g. skin lesions or lesions immediately under the skin), 6 MV FFF might provide a higher dose to the superficial target layers, whereas for deeper targets (beyond ~5 cm depth), 10 MV FFF could yield better penetration and dose uniformity to the distal target. However, one must balance this with other factors like higher out-of-field photon energy (which could increase neutron contamination at >10 MV, although 10 MV is usually below significant neutron production thresholds) and dose to skin. Fortunately, our data shows the skin dose for 10 MV FFF is actually lower than 6 MV FFF for the same setup, which could be beneficial for sparing surface tissues [9].

2. **Lateral Profiles and Flatness:** Both 6 MV and 10 MV FFF beams exhibited non-flat profiles, as expected due to the lack of a flattening filter. The magnitude of the off-axis fall-off was similar for the two energies in small fields - on the order of a few percent across the field width. For larger fields (approaching 10×10), we would expect the 10 MV FFF to have a slightly more peaked profile than 6 MV FFF (since higher energy photons are more forward directed); indeed, our measured flatness for 10×10 was ~107% vs~106% for 6×6 (in line with Narayanasamy et al. who reported~106.7% vs 105.7% for 10FFF vs 6FFF [7]). But

in the ≤5×5 cm range, the profiles are predominantly peak- less because the field is mostly within the central build-up region of the beam. A practical outcome here is that profile measurements in small fields did not reveal any problematic energy-dependent dose distribution differences. The symmetry being excellent indicates the MLC and head setup are well-aligned for both energies. The small difference in penumbra (~0.5 mm larger for 10 MV FFF) is likely not clinically meaningful in most scenarios, especially considering the precision of patient alignment is usually on the order of 1 mm or more. However, in stereotactic radiosurgery, where margins are minimal, even these subtle differences can slightly affect dose gradients at the field edges. Treatment planners might observe that 10 MV FFF beams have marginally wider field coverage for the same nominal field size. This could be accounted for in planning by checking the dose fall-off outside the target. Our validation against golden data also suggests that the TPS beam model accurately captures these profiles, which is reassuring; the gamma pass rates >99% imply no significant model deviations. Past studies have cautioned that some detectors (like diodes vs chambers) can read different penumbra widths due to volume effect [1], but our use of CC01 and water phantom scanning yields data that matches the reference, indicating CC01's spatial resolution was sufficient for these field sizes. Output Factors and Detector Considerations: The relative output factor results highlight how critical it is to use an appropriate detector and methodology. Our CC01 chamber results were in very close agreement with the golden data, meaning Elekta's reference presumably relies on small diodes or Monte Carlo. Achieving this agreement gives confidence that CC01 (with careful technique) is a valid choice for small- field output calibration on Versa HD. If a larger chamber had been used without correction, one would expect an underestimation of small-field output (due to volume averaging), which could lead to discrepancies of several percent. This is why the TRS-483 Code of Practice recommends detectors like CC01, micro- diamonds, or unshielded diodes for fields around 1-2 cm. In our case, the CC01's small size likely needed only minimal correction (if any). The slight difference at 2×2 cm (measured 0.83 vs golden 0.85) could hint at a small volume effect or positioning uncertainty-TRS-483 provides a field output correction factor kfclin, Qref clin ref for various detectors; for CC01 at 2×2 cm fields these factors are on the order of 1.01-1.02 for 6MV [1], which might explain a part of the difference. We essentially see that our data falls within those expected tolerances.

It is also worth discussing the energy trend in output factors. We noted a tiny drop (a few percent) in going from 6FFF to 10FFF for the smallest field. This aligns with intuitive expectations and some literature. A study by Das et al. on small field dosimetry noted that beam quality ($TPR_{20}/_{10}$) can influence output factor via changes in scattered dose components [7][15]. Additionally, recent work by Lechner et al. found that detectors require slightly different correction factors at different energies even for the same field size, especially at 18 MV vs 6 MV [14] (which is a much larger gap than 6 vs 10 MV). Our energy gap is moderate, and indeed the effect we see is modest. The implication for clinics is that beam data should be acquired for each energy separately - one cannot assume that small-field outputs at 10 MV FFF can be inferred from 6 MV FFF or vice versa by theoretical scaling. This might sound obvious, but it is sometimes tempting to reduce measurements by assuming similar shapes. Our results, along with those of other authors [7], clearly show that for commissioning high-accuracy stereotactic beams, each energy's dataset needs to stand alone. The good news is that our multi- energy comparison did not uncover any anomalous behavior that would complicate modeling - both energies behave like well- behaved photon beams with FFF characteristics. The differences are largely accounted for by first principles (attenuation, scatter) and are smoothly varying with field size and depth.

1. **Comparison with Flattened Beams:** While our study did not directly measure flattened beams, it's useful to contextualize our results with the broader picture. Flattened 6 MV beams typically have a slightly higher d_max (~1.5 cm) and higher dose at depth=10 (around 67-68%) than our 6 MV FFF, as seen in [Table 1], (they were almost the same at 5-10 cm though) [7]. Flattened 10 MV similarly would have PDD (10) ~73% (very close to 72.9% of 10FFF) but a bit higher at 20 cm (maybe ~46% vs 45% for FFF) [7]. The point is, flattening filter removal didn't drastically alter percent depth doses for these field sizes - it mainly affects the profile shape and out-of-field dose. But in small fields, even flattened beams don't have flat profiles, so the distinction blurs. We can infer that if we had measured 6 MV and 10 MV with flattening filters for 1×1-5×5 fields, the outputs and PDDs would be quite similar to the FFF case, except the absolute output factors for 1×1 might be slightly lower (because the flattening filter steals some primary fluency that is not compensated for by a large field in small fields, leading to lower relative output). In fact, our reference commissioning data indicates the range of output factors compressed by~18% for 6FFF vs 6FF and ~23% for 10FFF vs 10FF [1][7], meaning FFF beams have relatively higher small field output. This can be seen in the values: 10 MV flattened had 0.65 for 1 cm field vs 10 MV FFF 0.70 [1]. Therefore, one advantage of FFF mode is slightly improved output for tiny fields (at both energies). Combined with their higher dose rate, FFF beams are thus quite advantageous for stereotactic treatments.

2. **Clinical Implications:** For stereotactic treatments that use small, often numerous fields or arcs, the choice of beam energy can be important. Our results confirm that 10 MV FFF beams will deliver a higher fraction of dose at depth, which can improve target coverage in situations where the tumor is deep-seated or behind a significant depth of tissue. On the other hand, if treating a very superficial target (e.g., brain metastasis right at the skull surface or a shallow spinal lesion), 6 MV FFF might achieve the desired dose with less concern about sparing the very surface, since it inherently deposits more dose up-front (which is beneficial for the target but could be detrimental for skin if skin is not target). The lower surface dose of 10 MV FFF [9] could be advantageous for skin sparing when the target is deeper. Additionally, 10 MV beams have slightly higher penetration which might reduce the number of beams or angles needed to get dose coverage, at the cost of a bit more leakage or head scatter (though FFF mitigates head scatter by removing the flattening filter mass).

One must also consider beam matching and treatment planning system (TPS) modeling. The excellent match we found with golden beam data means our TPS (Monaco) can be commissioned with either using these measured data or directly the golden data with minimal adjustments. The gamma analysis >99% pass indicates that the machine is essentially delivering the golden beam within tight tolerances [1], which is a testament to Elekta's beam-matching and our careful calibration. This boosts confidence that patients treated with either energy will receive the dose as planned. It also simplifies any future validation or audits, as our data could serve as a reference for others. In fact, multi-center studies show remarkably small standard deviations in output factors for matched linacs of the same model and energy - on the order of <1% for fields ≥2×2 cm² [16][17]. Our data contributes to that body of evidence by demonstrating consistency with the Elekta reference and can reassure that no unusual discrepancies (such as an MLC transmission issue or an energy tuning problem) are present.

LIMITATIONS

We limited our measurements to square fields defined by the MLC. In clinical practice, very small fields may also be shaped by cones (for SRS) or irregular apertures. The dosimetric characteristics could differ slightly in those scenarios; for example, circular fields have different penumbra and output properties. Additionally, we did not measure extremely small fields below 1×1 cm² - primarily due to detector limitations - though modern protocols often extend down to 0.5 cm. At those sizes, diodes or film might be required. However, 1×1 cm² is a reasonable lower bound for most linac-based SRS after considering the effects of the tongue-and- groove and leaf positioning. Another limitation is that we focused on open field dosimetry. Many stereotactic treatments use modulated fields or composite fields. The small-field data is still the backbone for commissioning those, but interplay of multiple small fields (IMRT/VMAT) could introduce additional considerations (like dose linearity at small MU, MLC latency etc.), which were outside our scope. Our study also did not deeply delve into uncertainties - while we qualitatively mention them, a rigorous uncertainty analysis could be beneficial especially for output factors. That said, given our results match the reference so closely, any systematic error would likely have been evident as a bias relative to golden data.

CONCLUSION

We conducted a detailed dosimetric comparison of 6 MV FFF and 10 MV FFF photon beams for small field sizes on an Elekta Versa HD linac, including PDDs, lateral profiles, and output factors, with validation against manufacturer-provided golden beam data. The 10 MV FFF beam was found to have a deeper depth of maximum dose (~2.4 cm vs ~1.8 cm for 6 MV FFF) and a higher percentage depth dose at depths beyond ~5 cm, confirming the improved penetration of the higher energy beam [7]. Conversely, the 6 MV FFF beam deposits slightly more relative dose in the build-up region, leading to higher surface dose than 10 MV FFF for identical setups [9]. Lateral dose profiles for both energies in small fields are sharply peaked (non-flat) and highly symmetric, with only minor differences: 10 MV FFF showed marginally broader penumbra (by about 0.5 mm) and a tiny increase in central profile peak compared to 6 MV FFF, but these differences are negligible in practical terms. The relative output factors Janrease significantly with field size for both energies; using 10×10 field normalization, a 1×1 cm² field has an output factor of roughly 0.67-0.70. Our measurements showed the 6 MV FFF 1×1 output factor to be about 0.69 and the 10 MV FFF about 0.67, indicating a small (~3%) reduction at higher energy. All measured data were in excellent agreement with Elekta's golden beam reference, with over 99% of points passing 2%/2mm gamma criteria and output factor differences within 1-2% [1]. This high level of agreement validates the commissioning of our Versa HD for both FFF energies and demonstrates that the CC01 ion chamber, along with appropriate scanning techniques, can accurately characterize small fields in FFF beams. In summary, the effect of beam energy on small-field dosimetry in our study is quantitatively modest but noticeable: the higher energy 10 MV FFF beam provides better depth-dose performance (beneficial for deep targets) while the lower energy 6 MV FFF gives a slight boost in dose near the surface (useful for shallow targets), and both exhibit comparable lateral dose distributions and output scaling in small fields. Clinically, either energy can be used for stereotactic treatments on the Versa HD with confidence that the dose can be delivered accurately as modelled. The choice may ultimately depend on specific case requirements - for example, 10 MV FFF might be preferred in SBRT for deep abdominal tumors to ensure adequate penetration, whereas 6 MV FFF could be advantageous for brain lesions near the skull to avoid underdoing the superficial portion. Our results also reinforce the importance of verifying small-field beam data against reliable references: by confirming our measurements with the golden beam data, we ensure our TPS commissioning is sound and we add to the evidence base that well- configured treatment machines can reproduce the vendor's reference beam models within a very tight tolerance [1]. Future work could explore even smaller apertures, the use of advanced detectors like silicon diodes or microdiamond for cross- validation, and the interplay of FFF beam energy with modulated small fields. Nonetheless, the current findings provide a robust scientific basis for understanding and utilizing 6 MV FFF and 10 MV FFF beams in high-precision radiotherapy involving small fields.

REFERENCES

1. Alami OM. Small-Field Dosimetry on Elekta Versa HD: Comparative Evaluation of IBA CC01 and CC04 Chambers Against Golden Beam Data. Oncology and Radiotherapy. 2025; 19: 001–008.
2. Bagheri H. An overview on small-field dosimetry in photon beam radiotherapy: Developments and challenges. Journal of Medical Physics. 2017; 42: 59–69.
3. Das IJ, Ding GX, Ahnesjö A. Small fields: Nonequilibrium radiation dosimetry. Medical Physics. 2008; 35: 206–215.
4. Palmans H. Dosimetry of small static fields used in external photon beam radiotherapy: Summary of TRS-483. Medical Physics. 2018; 45: e1123–e1145.
5. Alfonso R. A new formalism for reference dosimetry of small and nonstandard fields. Medical Physics. 2008; 35: 5179–5186.
6. IAEA; AAPM. TRS-483: Dosimetry of small static fields used in external beam radiotherapy. International Atomic Energy Agency. 2017.
7. Narayanasamy G. Commissioning an Elekta Versa HD linear accelerator with high dose rate flattening filter free photon beams. Journal of Applied Clinical Medical Physics. 2016; 17: 179–191.
8. Yan Y. Dosimetric differences in flattened and flattening filter-free beam treatment plans. Journal of Medical Physics. 2016; 41: 92–99.
9. Rizk A. Evaluation of dosimetric parameters for flattening filter free photon beams in radiotherapy for two recent linear accelerator machines. Journal of Radiation and Nuclear Applications. 2025; 10: 95–101.
10. Yabsantia S. Determination of field output correction factors of radio photoluminescence glass dosimeter and CC01 ionization chamber and validation against IAEA-AAPM TRS-483 code of practice. Physica Medica. 2021; 89: 113–121.
11. Lechner W. Detector comparison for small field output factor measurements in flattening filter free photon beams. Radiotherapy and Oncology. 2013; 109: 356–360.
12. Nelms BE. A survey on planar IMRT QA analysis. Journal of Applied Clinical Medical Physics. 2007; 8: 76–90.
13. Low DA. Evaluation of the gamma dose distribution comparison method. Medical Physics. 2003; 30: 2455–2464.
14. Ringholz J. Small field output correction factors at 18 MV. Medical Physics. 2023.
15. Nguyen THT. Effect of an integral quality monitor on 4-, 6-, 10-MV, and 6-MV flattening filter-free photon beams. Journal of Applied Clinical Medical Physics. 2020; 22: 260–270.
16. Lechner W. A multinational audit of small field output factors calculated by treatment planning systems used in radiotherapy. Physics and Imaging in Radiation Oncology. 2018; 5: 56–63.
17. Dufreneix S. Field output factors for small fields: A large multicentre study. Physica Medica. 2021; 81: 191–196.