RADIATION ONCOLOGY PHYSICS

WILEY

Beam energy metrics for the acceptance and quality assurance of Halcyon linear accelerator

Song Gao[1] | Mikhail A. Chetvertkov[2] | Bin Cai[3] | Abhishek Dwivedi[4] |
Dimitris Mihailidis[5] | Xenia Ray[6] | Tucker Netherton[1] | Laurence E. Court[1] |
William E. Simon[7] | Peter A. Balter[1]

[1]Department of Radiation Physics, The University of Texas MD Anderson Cancer Center, Houston, TX, USA

[2]GenesisCareUS, Madison Heights, MI, USA

[3]Radiation Oncology, Washington University School of Medicine, St. Louis, MO, USA

[4]Radiation Oncology, Rutgers CINJ/Robert Wood, Johnson University Hospital, New Brunswick, NJ, USA

[5]Radiation Oncology, University of Pennsylvania, Philadelphia, PA, USA

[6]Radiation Medicine and Applied Science, University of California San Diego, Moores Cancer Center, La Jolla, CA, USA

[7]Sun Nuclear Corporation, Melbourne, FL, USA

Author to whom correspondence should be addressed. Song Gao
E-mail: songgao@mdanderson.org;
Telephone: (713) 563-2577; Fax: (713) 563-2545.

Abstract

Purpose: Establish and compare two metrics for monitoring beam energy changes in the Halcyon platform and evaluate the accuracy of these metrics across multiple Halcyon linacs.

Method: The first energy metric is derived from the diagonal normalized flatness (F_{DN}), which is defined as the ratio of the average measurements at a fixed off-axis equal distance along the open profiles in two diagonals to the measurement at the central axis with an ionization chamber array (ICA). The second energy metric comes from the area ratio (AR) of the quad wedge (QW) profiles measured with the QW on the top of the ICA. Beam energy is changed by adjusting the magnetron current in a non-clinical Halcyon. With D_{10cm} measured in water at each beam energy, the relationships between F_{DN} or AR energy metrics to D_{10cm} in water is established with linear regression across six energy settings. The coefficients from these regressions allow $D_{10cm}(F_{DN})$ calculation from F_{DN} using open profiles and $D_{10cm}(QW)$ calculation from AR using QW profiles.

Results: Five Halcyon linacs from five institutions were used to evaluate the accuracy of the $D_{10cm}(F_{DN})$ and the $D_{10cm}(QW)$ energy metrics by comparing to the D_{10cm} values computed from the treatment planning system (TPS) and D_{10cm} measured in water. For the five linacs, the $D_{10cm}(F_{DN})$ reported by the ICA based on F_{DN} from open profiles agreed with that calculated by TPS within $-0.29 \pm 0.23\%$ and 0.61% maximum discrepancy; the $D_{10cm}(QW)$ reported by the QW profiles agreed with that calculated by TPS within $-0.82 \pm 1.27\%$ and -2.43% maximum discrepancy.

Conclusion: The F_{DN}-based energy metric $D_{10cm}(F_{DN})$ can be used for acceptance testing of beam energy, and also for the verification of energy in periodic quality assurance (QA) processes.

PACS
87.55.Qr, 87.56.Fc

KEY WORDS
acceptance and QA, Halcyon linear accelerator, ionization chamber array, monitoring energy

1 | INTRODUCTION

The Halcyon (Varian Medical Systems, Palo Alto CA) is a single-energy 6-MV flattening filter free photon beam machine, and the universal beam model in the Eclipse (Varian Medical Systems, Palo Alto CA) treatment planning system (TPS) is predefined for all Halcyon linear accelerators (linacs).

A recent study demonstrated that the Halcyon platform can be validated with an ionization chamber array (ICA) and a 1D water scanner (1DS) without the need for a 3D water scanning system.[1] The commissioning verification was based on the AAPM Medical Physics Practice Guideline for Commissioning and QA of External Beam Planning Systems (MPPG5.a).[2] The diagonal normalized flatness (F_{DN}), which is calculated from open beam profiles measured with an ICA, was verified as a metric for monitoring beam energy and was more sensitive and reproducible than the traditional percent depth dose (PDD) energy metric.[3,4] Another method for determining photon beam energy uses a quad wedge (QW) which consists of two pairs of copper wedge-shaped attenuators along each of the diagonal detector axes of the ICA, with the wedge pairs being symmetrically opposed and the thin sections toward the array center.[5] The energy metric from the QW is the area ratio (AR), which is defined as the cumulative of measurements from a span of detectors in the presence of wedges and normalized to the cumulative of measurements from a similar detector set on the X and Y axes (open field profiles).[5]

The purpose of this study was to establish a legitimate ICA method for D_{10cm} verification for the Halcyon linac for both commissioning and periodic quality assurance, without the cumbersome 1DS water tank.

1.A | Summary of terminology

F_{DN}: the diagonal normalized flatness, the ratio of the average measurements at a fixed off-axis equal distance along the profiles in two diagonals to the measurement at the central axis.

QW: a quad wedge plate consists of two pairs of copper wedge-shaped attenuators along each of the diagonal detector axes.

AR: the area ratio (AR) which is defined as the sum of ICA measurements from a span of detectors under a quad wedge (QW) and normalized to the sum of measurements from a similar detector set on the X and Y axes (open field profiles).

D_{10cm}(water): Percent depth dose (PDD) at depth 10 cm, measured in water with 1D scanner (1DS). For simplicity, we use D_{10} denote D_{10cm} hereafter in the text.

D_{10}(TPS): PDD at 10 cm computed from the treatment planning system (TPS).

D_{10}(F_{DN}): PDD at 10 cm computed from F_{DN}, which is calculated from open beam profiles measured with an ICA.

D_{10}(QW): PDD at 10 cm computed from the AR with QW profiles measured using an ICA.

2 | MATERIALS AND METHODS

Both F_{DN}-based and AR-based energy metrics require calibration against a known energy metric that is chosen to be the percent depth dose (PDD) at a depth of 10 cm, D_{10}(water), measured in water at 90 cm source to surface distance (SSD). This setup matches that the vendor provided reference data which were specified at 90 cm SSD due to the geometry limit of the machine bore. To establish the relationships between F_{DN} and AR with D_{10} in water, beam energy is changed by adjusting the magnetron current in a non-clinical Halcyon corresponding to a change in beam energy from −10% to +5% off from its nominal value (Note that +10% produced an unstable beam). At each magnetron current setting, ICA measurements are acquired with an IC Profiler (Sun Nuclear, Melbourne FL) in open beam profiles and profiles with quad wedge (QW) (Sun Nuclear, Melbourne FL) for a maximum field size of 28×28 cm^2. In addition, PDDs were scanned in the 1D Scanner (1DS) (Sun Nuclear, Melbourne FL), providing a relationship between D_{10} and F_{DN} and AR, both calculated from the ICA measurements. Once these relationships are established with linear data fitting, D_{10} values can be calculated from D_{10}(F_{DN}) or D_{10}(QW), enabling future D_{10} measurements with only the ICA, without a water tank.

To evaluate the trueness of F_{DN}-based and AR-based energy metrics in predicting D_{10} values, open and QW beam profiles were measured with ICAs in five Halcyon linacs from five institutions under the same setup condition. D_{10}(F_{DN}) and D_{10}(QW) were calculated from the fitted functions from the non-clinical Halcyon linac and then compared with the D_{10}(water) and D_{10}(TPS) specific to each of the five clinical Halcyon linacs.

2.A | Measurement setup and procedure

The Halcyon is an inline magnetron linear accelerator with no bending magnet, the beam energy can be changed by adjusting the magnetron current. Without a direct means of determining how changes in magnetron current (MI) would change energy, previously determined relationships were used between changes in diagonal normalized flatness F_{DN} and changes in energy on a TrueBeam 6-MV FFF beam.[3] Each energy metric was measured at the nominal beam energy and at five intentionally created energy changes off −10.0%, −5.0%, −2.5%, +2.5%, and +5.0% from the nominal beam energy value (0%). After beam tuning to achieve stable dose rates and symmetric beam profiles for each MI setting, the beam parameters were saved to a file and later loaded for each tuned beam, which provided reproducible measurement setups.

Because the Halcyon does not have light field and radiation isocenter lasers, the ICA was set up in the following three steps[1]: (1) initial alignment with the outside bore lasers (virtual isocenter); (2) image guidance for final alignment with two orthogonal MV images; (3) acquisition of test profiles to verify the beam center and for fine-

tuning centering. The final positions for measurements with solid water buildup and the QW plate are illustrated in Fig. 1.

At each magnetron current setting, beam profiles were measured with an ICA with and without the QW. The ICA was then removed and PDDs were scanned with a 1DS with a 90-cm SSD for each energy.

2.B | Percent depth dose at changes in beam energy

PDD scans were obtained in a 1DS with SNC125c (Sun Nuclear, Melbourne FL) waterproof active volume of 0.125 cm^3 ion chambers and a PC electrometer (Sun Nuclear, Melbourne FL) by SNC dosimetry software. PDDs were scanned at six MI settings corresponding to the nominal beam energy and five intentional energy changes from the nominal energy. All PDD measurements were obtained at 90 cm SSD with 10 × 10 cm^2 field size at scanning depths ranging from 0 to 30 cm. The data were smoothed and renormalized to 100% by the values at d$_{max}$ for each energy.

2.C | ICA calibration and profile measurement

The detectors in the ICA were calibrated at the nominal beam energy on Halcyon linac at a detector depth of d$_{max}$ (1.4 cm = 0.9 cm inherent + 0.5 cm solid water), at an extended 110-cm SSD and 28 × 28 cm^2 field. The divergent field from the 100-cm SSD produced a 30.8 × 30.8 cm^2 field, which ensures that all detectors used in later measurements at 90 cm SSD were within the calibration field. The accuracy of the array calibration was evaluated according to previously proposed procedures,[6] and the calibration uncertainties were <0.5% for all detectors in the measurement field.

Beam profiles were measured for the maximum field size, with the ICA and at depth d$_{max}$, with 90 cm SSD. Profiles were measured on four axes, in-plane, cross-plane, and diagonals at six MI settings
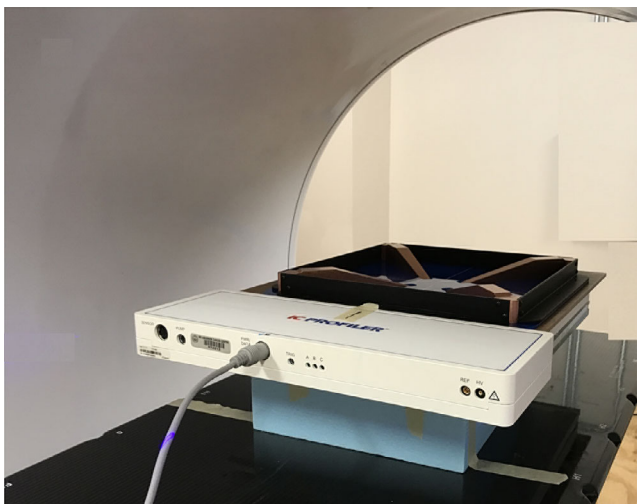

FIG. 1. The IC array measurement setup positions with solid water buildup and QW plate.

corresponding to the nominal beam energy and five intentionally created energy changes from the nominal energy, using the single calibration measurement at the nominal beam energy.

2.D | Beam energy metrics

The percent depth dose at 10 cm depth, D$_{10}$(water), from the PDD scanned in the water tank at 90 cm SSD with 10 × 10 cm^2 field size provided the standard energy metric.

2.D.1 | Diagonal normalized flatness energy metric

In beam profiles acquired with ICA, the diagonal normalized flatness is functionally related to beam energy and can be used as an energy metric.[3,4] The F$_{DN}$ values at different off-axis distances can be obtained from the open profiles through the IC PROFILER software. The off-axis points in the F$_{DN}$ are the points at the off-axis distances of approximately 90% and 60% of the maximum beam intensity, which are ±5.7 cm and ±15.6 cm, respectively, from the array center and located in a stable region of the profile. The relationship between D$_{10}$(water) and F$_{DN}$ from ICA measurement is calibrated by acquiring profiles at the six beam energies. A linear fit is determined between F$_{DN}$ and D$_{10}$(water) that can then be used to measure D$_{10}$ from F$_{DN}$ obtained from the ICA profile:

$$D_{10}(F_{DN}) = n \cdot F_{DN} + a, \quad (1)$$

where n and a are the slope and intercept values. Once this relationship is established, the D$_{10}$(F$_{DN}$) reports the value of D$_{10}$ at 90 cm SSD with 10 × 10 cm^2 field size.

2.D.2 | Quad wedge profile energy metric

Another method for determining photon beam energy is from the beam profiles acquired using ICA with a quad wedge (QW) on top of the ICA surface. The two wedge pairs in the QW plate are symmetrically opposed to the thin sections toward the array center (see Fig. 1). In beam profiles acquired with ICA and QW combination, the AR under the wedges is related to the beam energy, and thus the AR can be used as an energy metric.

The AR from the QW profiles is the sum of measurement data under the wedges (along diagonal axes) normalized to the sum of measurement data from a similar detector set on the X and Y axes (open field profiles)[5]:

$$AR = \frac{PD_{Area} + ND_{Area}}{X_{Area} + Y_{Area}}, \quad (2)$$

where PD$_{Area}$, ND$_{Area}$, X$_{Area}$, and Y$_{Area}$ represent the sum of corrected counts from the applicable detectors of the measured profiles for positive diagonal (PD), negative diagonal (ND), X, and Y axes, respectively.

The relationship between the measured AR and D$_{10}$(water) is established by determining the AR from the QW profiles at six beam energies with known D$_{10}$(water). A linear fit is determined between

AR and D_{10}(water), which can then be used to determine D_{10}(AR) from the measured profile with ICA/QW on a beam from the Halcyon linac:

$$D_{10}(AR) = m \cdot AR + b, \tag{3}$$

where m and b are the slope and intercept values and AR is the area ratio. Similar to $D_{10}(F_{DN})$, D_{10}(AR) also reports the value of D_{10} at 90 cm SSD with 10×10 cm^2 field size.

2.D.3 | Evaluation of beam energy metrics

Once the $D_{10}(F_{DN})$ and D_{10}(QW) metrics were established in the non-clinical Halcyon, meaning that the linear coefficients [eqs. (1) and (3), respectively] were derived from the calibrations, the IC Profiler software could report D10(F_{DN}) or D10(QW) from the measured open or QW profile, respectively. Five Halcyon linacs from five institutions were selected to study beam energy results by the methods D_{10}(water), D_{10}(TPS), $D_{10}(F_{DN})$, and D_{10}(QW). The D_{10}(water) and D_{10}(TPS) metrics were obtained on each institution's clinical Halcyon, as was used in the non-clinical Halcyon, and the D_{10}(TPS) was calculated with the institution's clinical Eclipse TPS.

$D_{10}(F_{DN})$ and D_{10}(QW) were calculated from their respective metrics in the five linacs at the institutions' nominal clinical beam energy. $D_{10}(F_{DN})$ and D_{10}(QW) were then compared with the measured PDD value D_{10}(water) and the calculated D_{10}(TPS). Their mean differences and corresponding standard deviations are presented below in the Results.

3 | RESULTS

3.A | Changes in percent depth dose

The PDD data were measured for 10×10 cm^2 field size with 90 cm SSD by the 1D water scanning system at the nominal clinical beam energy and at five energy changes from nominal (0%): −10.0%, −

5.0%, −2.5%, +2.5%, and +5.0%. The PDD curves were normalized to d_{max} depth for each energy, and an example of the effect of changes in beam energy on the changes in PDD curves is presented in Fig. 2. The D_{10} values of these six beam energies can be obtained from the PDD curves.

3.B | Changes in the profile

Beam profiles were measured at d_{max}, 90 cm SSD with a 28×28 cm^2 field size with and without QW, at the six beam energies (nominal clinical energy and five adjusted energy beams). The profiles were normalized to the corresponding central axis value for each beam energy, revealing the shape change in the profiles with the variation of the beam energy (Fig. 3).

3.C | Beam energy metrics

From the F_{DN} values at different off-axis distances and the corresponding D_{10}(water) values of the six beam energies, the linear fit parameters of the relationship between D_{10}(water) and F_{DN} are summarized in eqs. (4) and (5) (Fig. 4):

$$D_{10}(F_{DN}) = -0.807 \cdot F_{DN} + 133.3, \quad F_{DN} \text{ at } \pm 5.7 \text{ cm};'H'' \tag{4}$$

$$D_{10}(F_{DN}) = -0.476 \cdot F_{DN} + 90.1, \quad F_{DN} \text{ at } \pm 15.6 \text{ cm};'L'' \tag{5}$$

where H designates the high-intensity location on the profile and L the low-intensity location. $D_{10}(F_{DN})$ is calculated from the F_{DN} values measured with ICA by the equation above and compared with the D_{10}(water) values for all testing beams (Table 1). The $D_{10}(F_{DN})$ results from locations H and L have a maximum deviation ±0.02%.

From the AR values from the QW profiles and the corresponding D_{10}(water) values of the six beam energies, the linear fit parameters of the relationship between D_{10}(water) and AR are summarized in Eq. (6) (Fig. 5):
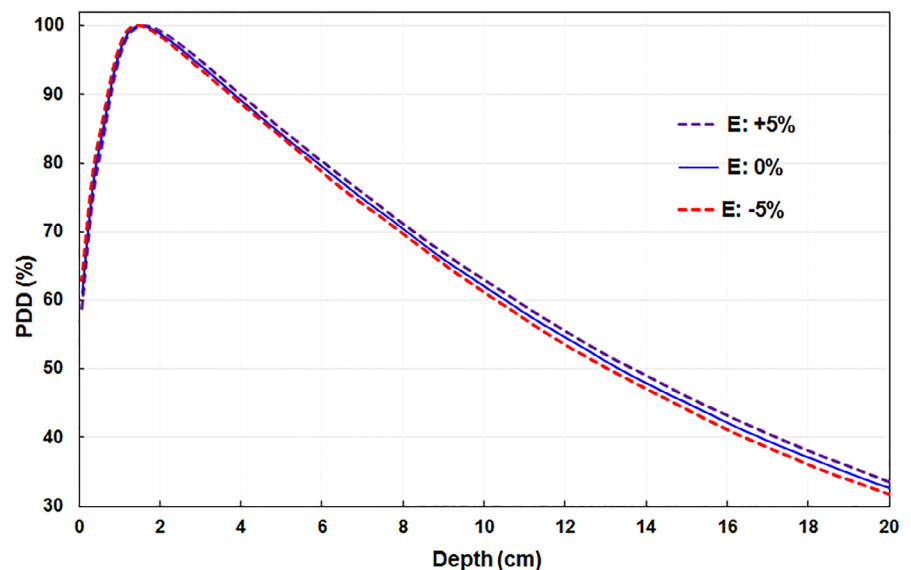

FIG. 2. The percent depth dose (PDD) scanned using the 1D water tank (shown for up to depth 20 cm only) with a source-to-surface distance (SSD) of 90 cm for field of 10×10 cm^2 for nominal beam energy (E: 0%), and energy changes +5% (E: +5%) and −5% (E: −5%) from nominal energy.
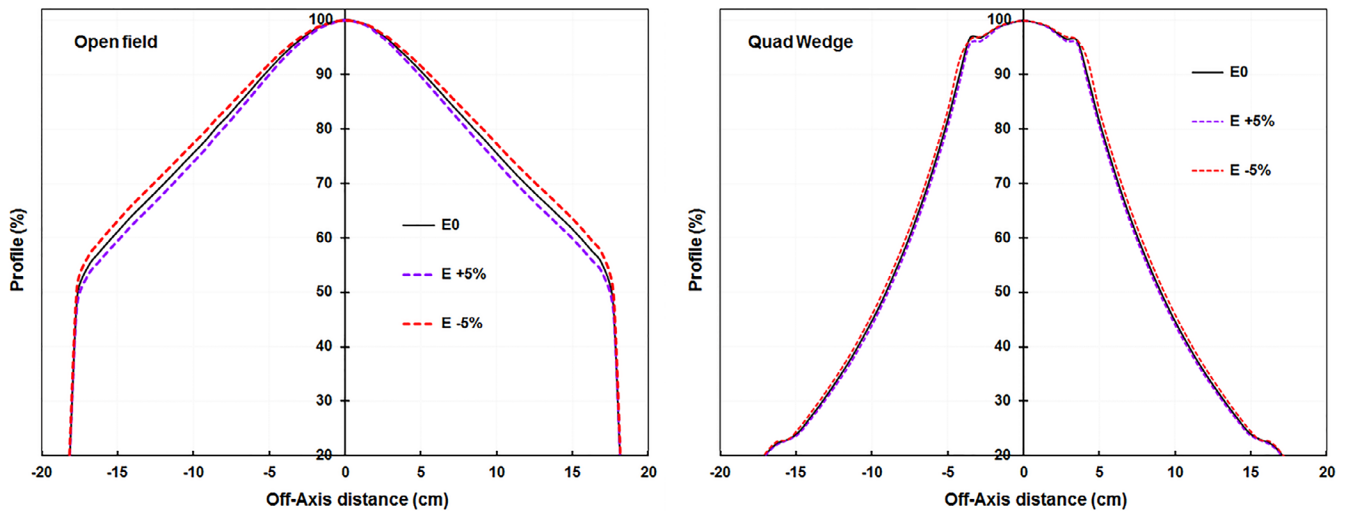
FIG. 3. Diagonal profiles measured with an ionization chamber profiler (ICA) with open field (left) or with quad wedge atop the ICA (right) for nominal beam energy (E: 0%), and energy changes +5% (E: +5%) and −5% (E: −5%) from nominal energy. The source-to-surface (SSD) is 90 cm, depth d_{max}, and the field size is 28×28 cm^2.
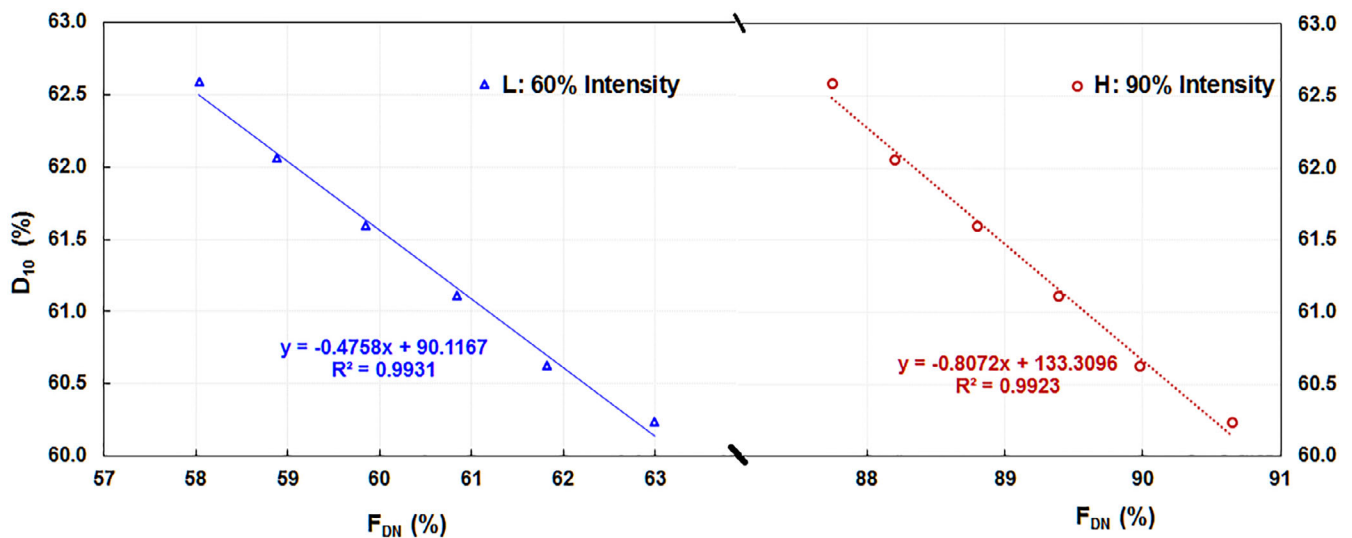

FIG. 4. The linear relationship between the percent depth dose at 10 cm depth D_{10} scanned with the 1D water scanner (1DS) and the diagonal normalized flatness (F_{DN}) measured from the beam profile with the ionization chamber array (ICA) for beam energies off the nominal beam energy by −10.0%, −5.0%, −2.5%, +2.5% and +5.0%. The off-axis distances are approximately 60% (L) and 90% (H) of maximum beam intensity.

$$D_{10}(QW) = 207.66 \cdot AR - 53.90. \tag{6}$$

With this calibration, the IC PROFILER software can report the $D_{10}(QW)$ values from the QW profiles. The $D_{10}(QW)$ values were compared with the corresponding $D_{10}(water)$ values for all six testing beams (Table 1). The differences are within 0.2%. It should be noted that the slope and intercept values in eqs. (4)–(6) are only valid for a field size of 28×28 cm^2 and SSD of 90 cm for profiles measured using ICA and the $D_{10}(water)$ values used for calibration were measured at a field size of 10×10 cm^2 and SSD of 90 cm in the water tank.

3.D | Evaluation of beam energy metrics

The measured $D_{10}(F_{DN})$ and $D_{10}(QW)$ values from five Halcyon linacs were compared with the measured $D_{10}(water)$ and calculated $D_{10}(TPS)$ values (Table 2).

The differences of D_{10} between F_{DN} and treatment planning (TPS) calculations $[D_{10}(F_{DN}) - D_{10}(TPS)]$ produced an average ± standard deviation (σ) of 0.29 ± 0.23%, with a range from 0.61% to −0.09%. Likewise, the differences $[D_{10}(F_{DN}) - D_{10}(water)]$ in D_{10} between F_{DN} and water scans $[D_{10}(F_{DN}) - D_{10}(water)]$ were an average of 0.22 ± 0.20%, with a range from 0.71% to −0.47%.

TABLE 1 Comparison of the percent depth dose at a depth of 10 cm (D_{10}), scanned with a 1D water scanning system, and the D_{10} values determined from the diagonal normalized flatness (F_{DN}) at two off-axis distances, 90% (H) and 60% (L) of maximum beam intensity, for five beam energies off the nominal energy (by −10.0%, −5.0%, −2.5%, 0%, +2.5% and +5.0%). Also shown are average values and differences (δ) for the difference in D_{10} between F_{DN} (average) and 1DS; the D_{10} determined from quad-wedge profile (QW); and differences in D_{10} between QW and 1DS. Data from one non-clinical Halcyon linac.

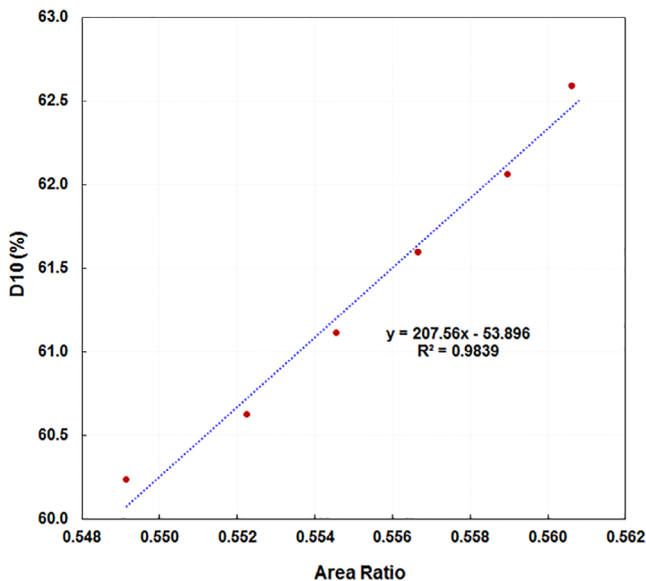| Change in energy (%)	5.0%	2.5%	0.0%	−2.5%	−5.0%	−10.0%
D_{10}(water), %	62.59	62.07	61.60	61.12	60.63	60.24
$D_{10}(F_{DN})$,%						
H	62.48	62.12	61.64	61.16	60.69	60.14
L	62.51	62.10	61.64	61.17	60.70	60.14
Average	62.49	62.11	61.64	61.16	60.69	60.14
δ (H–L)	−0.02	0.02	0.00	−0.01	−0.02	0.00
$\delta D_{10}(F_{DN}$-water)	−0.10	0.04	0.04	0.05	0.06	−0.10
D_{10}(QW),%	62.43	62.08	61.61	61.17	60.69	60.04
δD_{10}(QW-water)	−0.16	0.02	0.01	0.05	0.06	−0.20

FIG. 5. The linear relationship between the percent depth dose at 10 cm depth D_{10} scanned using the 1D water scanner (1DS) and the area ratio from the QW profile measured with the ionization chamber array (ICA) and QW plate for beam energies off the nominal beam energy by −10.0%, −5.0%, −2.5%, +2.5% and +5.0%.

Comparing D_{10} values determined from the QW profile to the TPS calculations and in-water measurements, the difference in D_{10} between the QW measurements and TPS calculations [D_{10}(QW) − D_{10}(TPS)] was an average ± standard deviation of 0.82 ± 1.27%, with a range from 2.43% to −0.60%. The difference in D_{10} between QW and in-water measurements [D_{10}(QW) − D_{10}(water)] was 0.22 ± 0.20%, with a range from 2.24% to −0.98%.

TABLE 2 The percent depth dose at a depth of 10 cm (D_{10}) determined from the diagonal normalized flatness (F_{DN}) and from the quad-wedge (QW) profile of five Halcyon linacs from five institutions. Also shown are the difference in D_{10} between F_{DN} and TPS (QW and TPS) and the difference in D_{10} between F_{DN} and water scans (QW and water scans), along with their averages and standard deviations (σ).

Method Machine	Off-axis ratio (F_{DN})			Quad Wedge (QW)		
	D_{10} (F_{DN})	δD_{10} (F_{DN}-TPS)	δD_{10} (F_{DN}-water)	D_{10} (QW)	δD_{10} (QW-TPS)	δD_{10} (QW-water)
M1	61.75	0.33	0.15	61.74	0.32	0.14
M2	62.03	0.61	0.18	63.85	2.43	2.00
M3	61.83	0.41	0.43	63.64	2.22	2.24
M4	61.61	0.19	0.71	61.12	−0.30	0.22
M5	61.33	−0.09	−0.47	60.82	−0.60	−0.98
Average	61.71	0.29	0.22	62.24	0.82	0.22
σ	0.23	0.23	0.20	1.27	1.27	0.20

In summary, results from each of the five Halcyon linacs tested indicate that the D_{10} values determined by F_{DN} from the open beam profiles agree with TPS calculations and in-water measurements within 0.8% for all linacs; and the D_{10} values determined by the QW profiles agree with TPS calculations and in-water measurements within 1.0% for three linacs but up to 2.4% for two linacs. This discrepancy could come from the differences in collimator scatter and/ or electron contamination in the low buildup region of the detectors, especially detectors in the X and Y axes.

4 | DISCUSSION

The Halcyon linac and the associated Eclipse TPS model are provided as an integrated system with no user-specific beam modeling capability, and thus the data collection at the time of acceptance testing and subsequent commissioning can be restricted to the need to verify rather than to create the TPS model.[1,7] A 2D ionization chamber array (ICA) can be used to measure changes in the energy of photon beams with a higher sensitivity than with PDD measurements.[3,4] This work demonstrated that with proper calibration, the diagonal F_{DN} measured with the ICA can be used to predict D_{10} that matched the TPS calculation and PDD water tank data. The measured D_{10}(QW) values also agreed reasonably well with the TPS calculation and the in-water measurement.

To examine the uncertainty of D_{10} values from linear regression, we excluded the minimum and the maximum points which are not fit the linear regression lines very well in Figs. 4 and 5. We obtained better coefficient of determination R^2 in the linear fit, $D_{10}(F_{DN}) = -0.4885\ F_{DN} + 90.8326$, $R^2 = 0.9999$) and $D_{10}(F_{DN}) = -0.8106\ F_{DN} + 133.5704$, $R^2 = 0.9998$ corresponding to L: 60% intensity and H 90% intensity in Fig. 4, respectively. We calculated the $D_{10}(F_{DN})$ values of all five linacs using these new linear fit equations. The difference of $D_{10}(F_{DN})$ values between the previous linear fit and the new

linear fit (minimum and the maximum points excluded) is $-0.04 \pm 0.01\%$ with a maximum of -0.05%. Similarly, for quad-wedge-based profile metric, we obtained $D_{10}(QW) = 214.5833AR - 57.8710$, $R^2 = 0.9994$ after excluded the minimum and the maximum points in the linear fit from the QW profiles (corresponding to Fig. 5). We calculated the $D_{10}(QW)$ values of all five linacs using this new linear fit. The difference of $D_{10}(QW)$ values between the previous linear fit and the new linear fit (minimum and the maximum points excluded) is $-0.03 \pm 0.07\%$ with a maximum of 0.13%.

For beam energy verification, although the diagonal F_{DN} method and QW profile method gave similar results for the non-clinical linac used for calibrations, the diagonal F_{DN} method showed better agreement than the QW method to TPS and in-water data for all other tested linacs. The QW method integrates selected detectors along the portion of diagonal axes under the QW and divides that by a selected portion of detectors along the X and Y axes, resulting in an "Area Ratio." The detectors along the portion of diagonal axes and along the X and Y axes have different collimator scatter and/or electron contamination in the low-buildup region because of differences in the thickness of wedge material or no wedge, which could introduce measurement uncertainty. The F_{DN} method is preferred because it does not require an additional device, and measurements and array calibration are done under the same buildup condition. In the quad-wedge profile method, the ICA array calibration was performed without a quad-wedge plate on top of the ICA, but the quad-wedge plate was in the beam path during the measurement. The copper wedge attenuates beam intensity as well as generating scatter radiation, which could increase measurement uncertainty. According to TG 142 recommendations,[8] X-ray beam quality D_{10} should be $\pm 1\%$ from baseline in annual QA checks. The D_{10} from F_{DN} metric has variation within this tolerance level, and the D_{10} from QW metric variation is outside this window. For simplicity and clean data acquisition, we recommend using the diagonal F_{DN} method for energy verification.

5 | CONCLUSIONS

The diagonal normalized flatness (F_{DN}) from the ICA beam profile energy metric and QW profile-based energy metric were established for Halcyon. The uncertainty analyses indicated the maximum linear fit induced error in $D_{10}(F_{DN})$ is less than 0.06%, and in $D_{10}(QW)$ is less than 0.14% which is not significant. The results of applying these independent energy metrics to five Halcyon linacs from five institutions demonstrated that the F_{DN}-based energy metric $D_{10}(F_{DN})$ is better matched to the $D_{10}(TPS)$ and $D_{10}(PDD)$ values than those measured with the quad-wedge profile-based energy metric $D_{10}(QW)$. The energy metric $D_{10}(F_{DN})$ can be used for acceptance of beam energy, for verification of energy in periodic QA testing, and also greatly speeds up the acceptance and QA processes.

AUTHOR CONTRIBUTIONS

Peter A. Balter, Song Gao, William E. Simon, Laurence E. Court: designed the study. Song Gao, Mikhail A. Chetvertkov, Bin Cai, Abhishek Dwivedi, Dimitris Mihailidis, Xenia Ray, Tucker Netherton: collected beam data and analyzed results. Song Gao, William E. Simon, Dimitris Mihailidis: wrote this manuscript. All contributing authors: edited this manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

1. Gao S, Netherton T, Chetvertkov MA, et al. Acceptance and verification of the Halcyon-Eclipse linear accelerator-treatment planning system without 3D water scanning system. *J Appl Clin Med Phys*. 2019;20(10):111–117.
2. Smilowitz JB, Das IJ, Feygelman V, et al. AAPM Medical Physics Practice Guideline 5a: Commissioning and QA of Treatment Planning Dose Calculations — Megavoltage Photon and Electron Beams. *J Appl Clin Med Phys*. 2015;16:14–34.
3. Gao S, Balter P, Rose M, Simon W. A comparison of methods for monitoring photon beam energy constancy. *J Appl Clin Med Phys*. 2016;17:242–253.
4. Goodall S, Harding N, Simpson J, Alexander L, Morgan S. Clinical implementation of photon beam flatness measurements to verify beam quality. *J Appl Clin Med Phys*. 2015;16:340–345.
5. Tirpak L, Simon T, Shi J, Simon W, Main B, Pawlak D, Mallia P. Beam Quality Verification Using IC Profiler with Quad Wedge Accessories. Varian Customer Technical Bulletin P1018976 DWG NO. GE-1013. Available at: https://www.sunnuclear.com/documents/publications/beam_quality_verification_using_ic_profiler.pdf (accessed 04/26/2021).
6. Gao S, Balter P, Tran B, Rose M, Simon W. Quantification of beam steering with an ionization chamber array. *J Appl Clin Med Phys*. 2018;19(3):168–176.
7. Netherton T, Li Y, Gao S, et al. Experience in commissioning the Halcyon linac. *Med Phys*. 2019;46:4304–4313.
8. Klein EE, Hanley J, Bayouth J, et al. Task Group 142 report: quality assurance of medical accelerators. *Med Phys*. 2009;36:4197–4212.