RADIATION ONCOLOGY PHYSICS

Monitoring linear accelerators electron beam energy constancy with a 2D ionization chamber array and double-wedge phantom

Song Gao | Mikhail A. Chetvertkov | William E. Simon | Amir Sadeghi | Peter A. Balter

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

Sun Nuclear Corporation, Melbourne, FL, USA

Radiation Oncology, Banner MD Anderson, Gilbert, AZ, USA

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

Present address
Mikhail A. Chetvertkov, Radiation Oncology, Allegheny General Hospital, Pittsburgh, CA, USA

Abstract
Validate that a two-dimensional (2D) ionization chamber array (ICA) combined with a double-wedge plate (DWP) can track changes in electron beam energy well within 2.0 mms as recommended by TG-142 for monthly quality assurance (QA). Electron beam profiles of 4–22 MeV were measured for a 25 × 25 cm² cone using an ICA with a DWP placed on top of it along one diagonal axis. The relationship between the full width half maximum (FWHM) field size created by DWP energy degradation across the field and the depth of 50% dose in water (R50) is calibrated for a given ICA/DWP combination in beams of known energies (R50 values). Once this relationship is established, the ICA/DWP system will report the R50FWHM directly. We calibrated the ICA/DWP on a linear accelerator with energies of 6, 9, 12, 16, 20, and 22 MeV. The R50FWHM values of these beams and eight other beams with different R50 values were measured and compared with the R50 measured in water, that is, R50Water. Resolving changes of R50 up to 0.2 cm with ICA/DWP was tested by adding solid-water to shift the energy and was verified with R50Water measurements. To check the long-term reproducibility of ICA/DWP we measured R50FWHM on a monthly basis for a period of 3 yr. We proposed a universal calibration procedure considering the off-axis corrections and compared calibrations and measurements on three types of linacs (Varian TrueBeam, Varian C-series, and Elekta) with different nominal energies and R50 values. For all 38 beams on same type of linac with R50 values over a range of 2–8.8 cm, the R50FWHM reported by the ICA/DWP system agreed with that measured in water within 0.01 ± 0.03 cm (mean ± 1σ) and maximum discrepancy of 0.07 cm. Long-term reproducibility results show the ICA/DWP system to be within 0.04 cm of their baseline over 3 yr. With the universal calibration the maximum discrepancy between R50FWHM and R50Water for different types of linac reduced from 0.25 to 0.06 cm. Comparison of R50FWHM values and R50Water values and long-term reproducibility of R50FWHM values indicates that the ICA/DWP can be used for monitoring of electron beam energy constancy well within TG-142 recommended tolerance.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2019 The Authors. Journal of Applied Clinical Medical Physics published by Wiley Periodicals, Inc. on behalf of American Association of Physicists in Medicine.
1 | INTRODUCTION

Periodic quality assurance (QA) of a clinical linear accelerator (linac) is important for dose accuracy during the treatment series of fractions. Deviations from baseline values acquired during commissioning\(^1\),\(^2\) or from the treatment planning system (TPS) should not exceed the TG or MPPG tolerance levels. Both AAPM Task Group 142\(^2\) and AAPM Medical Physics Practice Guideline (MPPG8.a)\(^3\) recommend that electron beam energy constancy be evaluated monthly and annually. However, there are no recommendations on how the QA tests should be performed and what equipment should be used. The electron beam energy quality metric, \(R_{50}\) Water, represents the depth at which the dose absorbed in water along the central beam axis, is reduced to 50% of its maximum value under full scatter conditions.\(^4\)

Electron beam energy constancy is traditionally measured with solid water slabs during monthly QA. This procedure can be time consuming and becomes tedious on a linac with multiple electron energies as different thicknesses of solid water slabs are required to characterize each electron energy. In addition, a recent study has shown that the tolerances for electron beam energy checks using a two-depth method are highly nonlinear due to the differences in gradient of the percent depth dose (PDD) falloff region.\(^5\)

The concept of monitoring electron energy with a combination of a wedge and a linear detector has been extensively studied. The first published work\(^6\) was by Moyer in 1981 who used an aluminum wedge placed on top of a radiographic film to measure electron beam energy constancy for beam energies from 6 to 18 MeV and showed an overall uncertainty of ±0.4 MeV. Rosenow et al. used one-dimensional (1D) ionization chamber array combined with a simple wedge-shaped polystyrene phantom to measure beam energies. They found that the full width at half maximum (FWHM) of the modified electron profiles correlated linearly with \(R_{50}\) in the whole range of energies studied.\(^7\) Using the same 1D ionization chamber array and similar wedge-shaped polystyrene phantom, Islam et al.\(^8\) were able to reproduce depth ionization curves in polystyrene phantom and the results agree quite well within water measurements for beam energy ≤10 MeV. Wells et al. used a home-made double-wedge acrylic phantom placed on top of a 1D diode array, and they found that the sensitivity of the combination of the diode array and double-wedge technique is similar to water-based depth-dose measurements.\(^9\) Other similar work has been done more recently using linear arrays combined with wedges for electron beam energy determination.\(^10\),\(^11\) The extensive studies published over the years on monitoring electron energy with wedge shape attenuators did not result in changes in clinical practice.

In this work, we validated a commercial system for monitoring changes in electron beam energy based on the principle of a wedge-shaped attenuator. The goal of this work was to ensure that a change in practice to use this device we will still meet the quality standards set out by the AAPM for electron beam energy stability (<2 mm uncertainty) while increasing our efficacy in performing QA. The system we are evaluating measures an electron beam energy constancy metric \(R_{50}\) using a two-dimensional (2D) ionization chamber array (ICA) (IC PROFILER, Sun Nuclear, Melbourne, FL) with an aluminum double-wedge plate (DWP) positioned on top of the ICA and the wedges along the positive diagonal axis. The double-wedge electron profiles are invariant to phantom alignment in the wedge direction for a given ICA/DWP combination. The relationship of the distance between the 50% dose points under each wedge, FWHM, is related to the \(R_{50}\) values in beams of known energies. Once this relationship is established the ICA/DWP system will report a beam energy which we will be referred to as \(R_{50}\)FWHM directly. We calibrated the \(R_{50}\) baseline with the ICA/DWP on a linear accelerator with energies of 6, 9, 12, 16, 20, and 22 MeV. We measured \(R_{50}\)FWHM with the ICA/DWP for the calibration beams and also for beam energies lowered by using plastic sheets to shift beam energies. In addition \(R_{50}\)FWHM data collected on a monthly basis on our clinical beams for a period of 3 yr during routine QA were used to evaluate the long-term stability of both the device and out beam energies.

We noted that the manufacture's calibration procedure neglected the off-axis ratio creating a calibration that was linac and beam dependent. We hypothesized that by removing the off-axis ratio from the calibration, subsequent measurements could make the calibration universal. To study this we used an alternative calibration procedure for the ICA/DWP. Instead of normalizing the double-wedge profile to the CAX, we normalized the double-wedge profile obtained along the positive diagonal axis to the unwedged profile along negative diagonal axis. We compared calibrations and measurements on three types of linacs (Varian TrueBeam, Varian C-series, and Elekta) with different nominal energies and \(R_{50}\) values.

The goal of this study was to evaluate the reproducibility of the electron beam energy metric \(R_{50}\)FWHM measured with the ICA/DWP. We examined the uncertainties and stability of the \(R_{50}\)FWHM values for known and unknown electron beam energies measured with the ICA/DWP and compared with measurements made with water scans. Measured \(R_{50}\)FWHM compared to the measured \(R_{50}\)Water showed good agreement for all electron beams in the study. We demonstrated that the ICA/DWP can be used for...
monitoring of electron beam energy constancy with high accuracy (<1 mm error) and reproducibility (<1 mm variation).

2 | MATERIALS AND METHODS

The 2D ICA used in this work is IC Profiler which has 251 ion chambers at an effective depth of 0.9 cm. The detectors are arranged along the four axes, cross-plane (x), in-plane (y), positive diagonal (PD), and negative diagonal (ND). The principal axes (x and y) are 32 cm in length with 0.5 cm detector spacing, while the diagonal axes (PD and ND) are 45 cm in length with 0.7 cm detector spacing. Array calibrations which normalize the relative response of the off-axis detectors to the central axis detector were performed initially on acceptance of the device and checked or repeated annually as per the manufactures' recommendation.\(^\text{12,13}\) The double-wedge used in this work is a pair of aluminum wedges affixed at opposite ends of the positive diagonal axis mounted on an acrylic plate which is placed on top of the ICA based on alignment marks (Sun Nuclear Corp.). The aluminum wedges are 10.7 cm long and have a height of 3.1 cm (Fig. 1). With the DWP in place on the ICA, the distance between the narrow ends of the wedges is 7.5 cm, which leaves the central axis of the beam unattenuated on the ICA. Prior to use of the array we validated the accuracy of the array calibration to be within a 0.5% maximum point-to-point deviation using published methods.\(^\text{14}\)

2.A | Calibration of electron beam energy metric \(R_{50}\)

In profiles acquired with a double-wedge, the off-axis distance (OAD) is directly related to the amount of aluminum that the beam has penetrated to reach the detectors. Thus the OAD that results in the signal being reduced to 50% of the value on the open central axis (OAD\(_{50}\)) can then be directly related to beam energy. Rather than using the OAD\(_{50}\) directly the ICA uses the full width at half maximum (FWHM) of the diagonal profile as its energy metric (Fig. 2). This minimizes the uncertainties associated with device setup. The relationship between \(R_{50}\) in water and FWHM for each ICA/DWP combination is calibrated by the user in their electron beams by acquiring double wedge profiles and determining the FWHM in a number of beams with known \(R_{50}\). A linear fit is determined between FWHM and \(R_{50}\) which can then be used to measure \(R_{50}\) on beams from linear accelerators of the same design (make/model). We performed the calibration procedure on a linear accelerator (TrueBeam, Varian Medical Systems, Palo Alto, CA, USA) with nominal energies of 6, 9, 12, 16, 20, and 22 MeV. For each beam used in calibration we captured a profile in a 25 \(\times\) 25 cm\(^2\) cone at 100 cm SSD with the DWP in place and associated this curve with the \(R_{50}\) for the same field. The data are used to determine a linear fit of \(R_{50}\) vs FWHM (x) [Eq. (1)].

\[
R_{50} = mx + b
\]

The ICA software (IC PROFILER Software V3.4 and later) has the calculation of the \(R_{50}\) to FWHM built in so once the relationship is established an \(R_{50}\) value is reported directly to the user.

2.B | Measurement of \(R_{50}\) with ICA/DWP and verified with water scans

All measurements were taken with the ICA/DWP at SSD of 100 cm with a 25 \(\times\) 25 cm\(^2\) electron cone. We measured \(R_{50}\)/FWHM values on the same linac with both the electron beams used for the calibration and with additional energies created by placing range shifters consisting of 0.075-, 0.150- and 0.225 cm solid-water in the beam path. To evaluate the accuracy of electron energy measured with the ICA/DWP, we compared \(R_{50}\) determined with the ICA/DWP to that measured in water from PDD scans for the nominal electron beams (6-, 9-, 12-, 16-, 18-, 20-, and 22-MeV) as well as the unknown energy beams. In addition, we measured the \(R_{50}\)/FWHM on two other TrueBeam linacs with energies of 6, 9, 12, 16, and 20 MeV, and compared the ICA/DWP \(R_{50}\)/Water values with those determined from water scans.

2.C | Reproducibility of \(R_{50}\) measured with ICA/DWP

To test the short-term reproducibility of the \(R_{50}\) measurement with ICA/DWP, we performed the measurement of each of the five electron beams on our Varian TrueBeam three times on the same day and analyzed the variation of the measurements. To verify the long-term reproducibility of ICA/DWP for monitoring electron beam energy, we measured \(R_{50}\) on a monthly basis for a period of 3 yr.
2.D | Calibrations and measurements of R$_{50}$ across types of linac

2.D.1 | Individual calibration and universal calibration

With the same calibration procedure and same measurement setup done on the TrueBeam (TB1) linac, we performed individual calibration on two other TrueBeam (TB2 and TB3), two Varain C-series linacs (Clinac1 and Clinac2), and two Elekta (Elekta, Inc. Stockholm, Stockholm, Sweden) linacs (Versa and Infinity), with different nominal energies and R$_{50}$ values (Table 1). The calibration results were exported from the ICA software and compared. We also investigated a modified “universal” calibration and measurement procedure by taking the off-axis ratios into consideration. This calibration procedure normalizes the positive diagonal double-wedge profile to the unwedged negative diagonal profile. This was accomplished by exporting the ICA/DWP profile data to excel and manually calculating the FWHM values to establish the linear relationship between R$_{50}$ and those FWHM values. This was done for each type of machine.

2.D.2 | Measurement of R$_{50}$ with individual and universal calibration

We used both linac specific calibrations and the universal calibration protocol to determine R$_{50}$ for a large number of beams on Varian TrueBeam and C-series machines as well as on the Elekta Versa and Infinity machines. We measured 38 beams on the TrueBeam with energies over the range of 6–22 MeV including ones obtained with the range shifters used in Section 2.B. We measured ten beams on the C-series machines with energies ranging from 4 to 20 MeV. We measured nine beams on the Elekta platforms with energies ranging from 6 to 18 MeV. For each type of machine we created an ICA/DWP calibration as per the vendor’s instructions. We also created a universal calibration for each type of machine for cross comparisons of all measurements. For each machine we examined the accuracy of R$_{50}$/FWHM values determined using the calibrations obtained on that type of machine, calibration obtained on the other types of machines, and using the universal method.

2.E | Flatness and symmetry measurements with and without DWP

To assess the influence of the double-wedge plate on the flatness and symmetry measurement in the principal axes we measured the profiles of nominal energy beams on the TrueBeam five times each with and without the double-wedge plate on top of the ICA with the same setup on the same day. We obtained the flatness and symmetry values of each beam with and without DWP on ICA, then evaluated if the DWP affected the results by comparing the measured flatness and symmetry.

Table 1 | The R$_{50}$ Water (cm) corresponds to the nominal beam energy for different types of the linac in this study.

| Energy (MeV) | 4  | 6  | 7  | 9  | 11 | 12 | 15 | 16  | 18  | 20  | 22  |
|------------|----|----|----|----|----|----|----|-----|-----|-----|-----|
| TrueBeam   | ×  | 2.39 | ×  | 3.53 | ×  | 4.94 | ×  | 6.60 | ×   | 8.27 | 8.78 |
| Clinac 1   | ×  | ×  | 3.22 | 3.83 | 4.52 | ×  | ×  | 6.40 | ×   | 8.39 | ×   |
| Clinac 2   | 2.07 | 2.65 | ×  | 3.84 | ×  | 5.08 | ×  | 6.49 | ×   | ×   | ×   |
| Versa      | ×  | 2.58 | ×  | 3.70 | ×  | 4.93 | 5.98 | ×   | ×   | ×   | ×   |
| Infinity   | ×  | 2.45 | ×  | 3.79 | ×  | 4.70 | 5.90 | ×   | 7.15 | ×   | ×   |
The reproducibility of the measurements was excellent (the standard deviation, $\sigma \leq 0.004$ cm).

### RESULTS

#### 3.A | Correlation of the ICA/DWP profile with beam quality metric $R_{50}$

The ICA/DWP calibration procedure was done using the 6, 9, 12, 16, 20, and 22 MeV electron beams on a Varian TrueBeam (TB1). The IC Profiler software determined a linear fit between the $R_{50}$ values in Table 1 and the measured FWHM of the acquired profiles. The linear approximation of $R_{50}$ Water and the FWHM ($\delta$) was: $R_{50}$ Water = $0.41154x - 1.90835$ ($R^2 = 0.99975$).

#### 3.B | $R_{50}$ measured with ICA/DWP and compared within water scans

$R_{50}$ FWHM and $R_{50}$ Water measurements were made on all electron beams (6-, 9-, 12-, 16-, 18-, 20-, and 22 MeV) on the same linac used for the calibration, the measurements were repeated three times, each time with an independent setup. The maximum difference in the $R_{50}$ FWHM and $R_{50}$ Water values was 0.04 cm (Table 2). The reproducibility of the measurements was excellent (the standard deviation, $\sigma \leq 0.004$ cm).

### Table 2

$R_{50}$ Water (cm) vs $R_{50}$ FWHM (cm) for nominal energy beams, mean ± standard deviations ($\sigma$), and their difference: $\delta R_{50} = R_{50}$ FWHM − $R_{50}$ Water.

| Energy | 6e | 9e | 12e | 16e | 18e | 20e | 22e |
|--------|----|----|-----|-----|-----|-----|-----|
| $R_{50}$ FWHM (cm) | 2.39 ± 0.004 | 3.53 ± 0.000 | 4.94 ± 0.004 | 6.59 ± 0.005 | 7.57 ± 0.004 | 8.26 ± 0.000 | 8.79 ± 0.000 |
| $R_{50}$ Water (cm) | 2.39 ± 0.002 | 3.53 ± 0.003 | 4.94 ± 0.003 | 6.60 ± 0.002 | 7.53 ± 0.003 | 8.27 ± 0.001 | 8.78 ± 0.002 |
| $\delta R_{50}$ (cm) | 0.00 | 0.00 | 0.00 | 0.00 | –0.01 | 0.04 | –0.01 |

Table 3

$R_{50}$ Water (cm) vs $R_{50}$ FWHM (cm) for energy shifted beams and their difference: $\delta R_{50} = R_{50}$ FWHM − $R_{50}$ Water.

| Energy | 6e | 9e | 12e | 16e | 18e | 20e | 22e |
|--------|----|----|-----|-----|-----|-----|-----|
| $R_{50}$ FWHM (cm) | 2.33 | 3.46 | 4.84 | 6.51 | 7.50 | 8.16 | 8.70 |
| $R_{50}$ Water (cm) | 2.32 | 3.45 | 4.86 | 6.52 | 7.45 | 8.19 | 8.71 |
| $\delta R_{50}$ (cm) | 0.01 | 0.01 | –0.02 | –0.01 | 0.05 | –0.03 | –0.01 |

#### 3.C | Long-term reproducibility of $R_{50}$ measured with ICA/DWP

Monthly measurements of $R_{50}$ FWHM on a single linear accelerator (TB1) for five electron beams over a 3-yr period were used to determine long-term stability. Histogram analysis of the $R_{50}$ differences between the nominal $R_{50}$ and $R_{50}$ FWHM indicated that 99.4% agreed within ±0.05 cm and 100% agreed within ±0.10 cm (Fig. 3). The standard deviations were <$0.014$ cm (Table 5).

For beams not used for calibration and which were created by using different thickness of solid-water as energy shifters, the maximum difference in the $R_{50}$ FWHM and $R_{50}$ Water values was less than 0.07 cm (Table 3). The reproducibility of those measurements was similar to that in nominal energy beams.

The $R_{50}$ values of the five nominal energy beams on two other linacs (TB2, TB3) of the same model used for the calibration had identical results with the beams on the linac used for calibration. The $R_{50}$ FWHM and $R_{50}$ Water ICA/DWP agreed within 0.04 cm (Table 4).

For all 38 beams of known and unknown energies for the same type of linacs, $R_{50}$ values measured using ICA with double-wedge plate and those measured in water showed good agreement. The $R_{50}$ FWHM values agreed with $R_{50}$ Water of 0.01 ± 0.03 cm (mean ± $\sigma$) and a maximum discrepancy of 0.07 cm.

### Table 4

$R_{50}$ Water (cm) vs with $R_{50}$ FWHM (cm) for nominal energy beams in other two TrueBeam linacs (TB2, TB3) and their difference: $\delta R_{50} = R_{50}$ FWHM − $R_{50}$ Water.

| Energy | 6e | 9e | 12e | 16e | 20e |
|--------|----|----|-----|-----|-----|
| $R_{50}$ FWHM (cm) | 2.38 | 3.60 | 4.98 | 6.65 | 8.26 |
| $R_{50}$ Water (cm) | 2.38 | 3.59 | 5.02 | 6.65 | 8.30 |
| $\delta R_{50}$ (cm) | 0.00 | 0.01 | –0.04 | 0.00 | –0.04 |

TB2, SD of $\delta R_{50}$ (cm) = 0.022 cm

TB3, SD of $\delta R_{50}$ (cm) = 0.024 cm

$R_{50}$ FWHM (cm) | 2.36 | 3.56 | 4.97 | 6.60 | 8.24 |
| $R_{50}$ Water (cm) | 2.32 | 3.54 | 4.99 | 6.62 | 8.24 |
| $\delta R_{50}$ (cm) | 0.04 | 0.02 | –0.02 | –0.02 | 0.00 |

For all 38 beams of known and unknown energies for the same type of linacs, $R_{50}$ values measured using ICA with double-wedge plate and those measured in water showed good agreement. The $R_{50}$ FWHM values agreed with $R_{50}$ Water of 0.01 ± 0.03 cm (mean ± $\sigma$) and a maximum discrepancy of 0.07 cm.

### 3.D | Calibrations and measurements of $R_{50}$ across types of linac

#### 3.D.1 | Individual calibration and universal calibration

The ICA/DWP calibration was performed on three Varian True-Beams, two Varian C-series with custom beam energies (Clinac1 and...
Clinac2) as well as on two Elekta machines, a Versa and an Infinity spanning a range of energies (Table 1). The slopes, intercepts, and Pearson coefficient for the calibrations for each linac was calculated by the SNC software (Table 6). Difference in the linear fits between the different linac types were dominated by the high-energy beams (Fig. 4(a)). The R_{50} values in water have good linear relationship with the FWHM. We only present data for energies ≥12 MeV to emphasize the differences of the ICA calibrations for different types of linac. For each beam on each linac we determined the discrepancy in R_{50,FWHM} vs R_{50,Water} when using the calibration done for that linac (Self), for another linac of the same type (Same Type), and for a linac of another type (Cross Type). We examined histograms of the differences [Fig. 5(a)] as well as quantifying the maximum difference for each linac across all beams. (Table 6). We found that “Self” calibration gave the best results with a maximum discrepancy of 0.07 cm, followed closely by “Same Type” calibrations with 0.08 cm with the worst results being “Cross Type” calibrations which had discrepancies of up to 0.25 cm.

**Table 5** The maximum difference (δR_{50}) between ICA/DWP measured R_{50} and their baselines R_{50,Water} and the standard deviation (σ) of R_{50} measured with ICA for five nominal energy beams over a period of 3 yr.

| Energy | 6e | 9e | 12e | 16e | 20e |
|--------|----|----|-----|-----|-----|
| δR_{50} (cm) | 0.040 | 0.020 | 0.010 | 0.020 | 0.020 |
| σ (cm) | 0.008 | 0.011 | 0.011 | 0.010 | 0.013 |

**Table 6** Individual calibrations from ICA software by linac type and their maximum difference: δR_{50,max} = R_{50,FWHM} − R_{50,Water} with different calibrations. “Self” indicates using the calibration determined on that particular linac. “Same Type” is on a linac of the same maker and model but not the same machine. “Cross Type” is using a calibration determined on a different maker and model of linacs.

| Linac      | Slope  | Intercept | R^2     | Self   | Same type | Cross type |
|------------|--------|-----------|---------|--------|-----------|------------|
| TB1        | 0.4115 | −1.9083   | 1.0000  | −0.07  | 0.07      | 0.18       |
| TB2        | 0.4181 | −1.9876   | 0.9998  | 0.04   | −0.06     | 0.15       |
| TB3        | 0.4134 | −1.9520   | 0.9996  | 0.00   | 0.05      | 0.15       |
| Clinac1    | 0.4218 | −2.0364   | 0.9993  | −0.02  | −0.08     | −0.18      |
| Clinac2    | 0.4194 | −1.9833   | 0.9994  | 0.02   | 0.08      | −0.11      |
| Versa      | 0.4258 | −2.0474   | 0.9999  | 0.00   | −0.05     | −0.25      |
| Infinity   | 0.4214 | −1.9991   | 1.0000  | 0.01   | 0.04      | −0.20      |

**Fig. 3.** Histogram distributions of the differences of R_{50} measured with the ionization chamber array with double-wedge and their baselines. These data represent 36 measurements for each of five electron beams. Measurements were performed on a monthly basis for a period of 3 yr.

**Fig. 4.** The R_{50} calibration based on the full width half maximum from the double-wedge profiles of electron beams with known R_{50} values. (a) Individual calibrations from ionization chamber array software, (b) universal calibration by considering off-axis corrections.
The universal calibration that takes into account off-axis corrections was also determined for each of these machines. The universal calibration resulted in the linear fits that were machine independent [Fig. 4(b)]. The discrepancies between $R_{50,FWHM}$ and $R_{50,Water}$ were slightly increased compared to the "Self" calibration, were equivalent to the "Same Type" calibration, and far superior to the "Cross type" calibration [Fig. 5(b)]. With the universal calibration, the maximum discrepancy between $R_{50,FWHM}$ and $R_{50,Water}$ for "Self" and "Same Type" was modestly reduced to 0.06 cm while the maximum discrepancy for the "Cross type" was dramatically reduced to also be 0.06 cm (Table 7) The improved agreement among slopes on the three linac types indicates the $R_{50,FWHM}$ measurement method may be linac invariant if performed with universal calibration.

### Table 7

| Linac | Slope   | Intercept | $R^2$ | Self  | Same type | Cross type |
|-------|---------|-----------|-------|-------|-----------|------------|
| TB1   | 0.4161  | −1.9887   | 0.9997| −0.06 | 0.06      | −0.06      |
| TB2   | 0.4158  | −1.9811   | 0.9998| 0.05  | −0.06     | −0.03      |
| TB3   | 0.4162  | −2.0178   | 0.9999| 0.05  | −0.04     | 0.01       |
| Clinac1| 0.4160  | −2.0256   | 0.9997| −0.05 | −0.05     | 0.03       |
| Clinac2| 0.4155  | −1.9998   | 0.9996| −0.05 | −0.05     | 0.05       |
| Versa | 0.4163  | −1.9889   | 0.9997| 0.03  | 0.03      | −0.02      |
| Infinity| 0.4139  | −1.9493   | 0.9998| 0.03  | 0.04      | −0.03      |

The universal calibration that takes into account off-axis corrections was also determined for each of these machines. The universal calibration resulted in the linear fits that were machine independent [Fig. 4(b)]. The discrepancies between $R_{50,FWHM}$ and $R_{50,Water}$ were slightly increased compared to the "Self" calibration, were equivalent to the "Same Type" calibration, and far superior to the "cross type" calibration [Fig. 5(b)]. With the universal calibration, the maximum discrepancy between $R_{50,FWHM}$ and $R_{50,Water}$ for "Self" and "Same Type" was modestly reduced to 0.06 cm while the maximum discrepancy for the "cross type" was dramatically reduced to also be 0.06 cm (Table 7) The improved agreement among slopes on the three linac types indicates the $R_{50,FWHM}$ measurement method may be linac invariant if performed with universal calibration.

### Table 8

| Energy | 6e   | 9e   | 12e  | 16e  | 18e  | 20e  | 22e  |
|--------|------|------|------|------|------|------|------|
| $\delta F$ (%) | −0.10 ± 0.00 | −0.04 ± 0.05 | 0.04 ± 0.03 | 0.00 ± 0.00 | 0.05 ± 0.00 | 0.00 ± 0.00 | 0.05 ± 0.00 |
| $\delta S$ (%) | −0.14 ± 0.05 | 0.08 ± 0.06 | 0.12 ± 0.04 | 0.07 ± 0.04 | 0.00 ± 0.00 | 0.11 ± 0.05 | −0.01 ± 0.05 |

**3.E | Flatness and symmetry measurements with and without DWP**

We measured flatness and symmetry of the principal axes ($x$ and $y$ axes) from the profiles acquired using ICA with and without the DWP. Five measurements were done for each case for each beam. The difference in measured flatness and symmetry with and without the DWP showed that the effects of the DWP were <0.10% on flatness and <0.15% on symmetry (Table 8). This is expected as the DWP does not block the detectors along principal axes.

**4 | DISCUSSION**

The traditional method of detecting changes in electron beam energy is by comparing the relative dose (signal) at a known depth (or thickness of plastic phantom) against a reference dose determined at the time of commissioning. This procedure is time consuming and becomes tedious for a multiple electron energy linac since different depths are required to characterize each electron energy. The flatness and symmetry measured from beam profiles are traditionally performed with 2D array (diode or ionization chamber) or film, which is another setup and measurement. Measuring changes in $R_{50}$ with an ionization chamber array combined with a double-wedge gives equivalent result as in water scans without requiring the user to change depths between energies as well as providing the flatness and symmetry measurement.

**Fig. 5.** Histogram distributions of the differences in $R_{50}$ full width half maximum with different calibrations and $R_{50,Water}$. “Self” indicates using the calibration determined on that particular linac, “Same type” is on a linac of the same maker and model but not the same machine, “Cross type” is using a calibration determined on a different maker and model of linacs. (a) Individual calibrations from ICA software, (b) universal calibration by considering off-axis corrections.
simultaneously. Compared to other approaches using 1D/2D planner array, the method examined in this work has advantages: (a) the setup is easy and the baseline calibration is straightforward; (b) the Profiler software can directly report the value of $R_{50}$; (c) the flatness and symmetry in principal axes and the beam energy $R_{50}$ can be measured in one profile acquisition. We have also demonstrated that a modification of the calibration procedure to include the off-axis corrections in the calibration would allow this ICA/DWP to directly determine $R_{50}$ on different beams/machine types universally.

Furthermore, photon beam energy constancy metric, previous studies have demonstrated that an ICA can be used to measure changes in the energy, characterized by off-axis ratio (e.g., in diagonal axes, diagonal normalize flatness, $F_{D\!\!N}$) with a higher sensitivity than can be achieved with percentage depth-dose measurements. Thus, we are able to replace both the photon and electron beam energy and profiles constancy measurements with a more efficient set of measurements using 2D IC array.

5 | CONCLUSIONS

A convenient method for constancy checks of electron beam energies is described based on a commercially available ion-chamber array and double-wedge plate. In a single setup, this method is capable of measuring beam energy as well as the flatness and symmetry for electron beams. The results compared with in water measurement and the long-term reproducibility indicated that the method of monitoring electron beam energy achieved an uncertainty level well below the clinical tolerance level of 2 mm. This combined with earlier published work on monitoring photon beam energy with similar device could be incorporated in routine QA procedures saving time while maintaining quality.

ACKNOWLEDGMENTS

The authors thank Jared Ohrt for Versa data acquisition and Michael Gillin for valuable discussions.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Kutcher GJ, Coia L, Gillin M, et al. Comprehensive QA for radiation oncology: Report of AAPM Radiation Therapy Task Group 40. Med Phys. 1994;21:581–618.
2. Klein EE, Hanley J, Bayouth J, et al. Task Group 142 report: quality assurance of medical accelerators. Med Phys. 2009;36:4197–4212.
3. Smith K, Balter P, Duho J, et al. Medical physics practice guideline 8.a.: linear accelerator performance tests. J Appl Clin Med Phys. 2017;18:23–39.
4. Almond PR, Biggs PJ, Coursey BM, et al. AAPM Task Group 51: protocol for clinical reference dosimetry of high energy photon and electron beams. Med Phys. 1999;26:1847–1870.
5. Meyer J, Nylot MJ, Smith WP, et al. Electron beam energy QA — a note on measurement tolerances. J Appl Clin Med Phys. 2016;17:249–257.
6. Meyer RF. Quality assurance of electron-beam energy using an aluminum wedge. Radiology. 1981;140:237–239.
7. Rosenow UF, Isham MK, Gaballa H, Rashid H. Energy constancy checking for electron beams using a wedge-shaped solid phantoms combined with a beam profile scanner. Med Phys. 1991;18:19–25.
8. Islam MK, Rashid H, Gaballa H, Ting J, Rosenow UF. A simple method of producing depth ionization data for electron energy constancy check. Med Phys. 1993;20:187–191.
9. Wells DM, Picco PJ, Anscher W. Electron energy constancy verification using a double-wedge phantom. J Appl Clin Med Phys. 2003;4:204–208.
10. Speight RJ, Esmail A, Weston SJ. Quality assurance of electron and photon beam energy using the BQ-check phantom. J Appl Clin Med Phys. 2011;12:239–244.
11. de la Vega JM, Ruiz-Arrebola S, Tornero-López AM, et al. A method to relate StarTrack®measurements to R50 variations in clinical linacs. Physica Med. 2014;30:827–832.
12. Simon TA, Simon WE, Kahler D, Li J, Liu C. Wide field array calibration dependence on the stability of measured dose distributions. Med Phys. 2010;37:3509–3509.
13. Simon TA, Kozelka J, Simon WE, Kahler D, Li J, Liu C. Characterization of a multi-axis ion chamber array. Med Phys. 2010;37:6101–6111.
14. 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;19:168–176.
15. Gao S, Balter P, Rose M, Simon W. Measurement of changes in linear accelerator photon energy through flatness variation using an ion chamber array. Med Phys. 2013;40:042101.
16. 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.
17. Gao S, Balter P, Rose M, Simon WE. A comparison of methods for monitoring photon beam energy constancy. J Appl Clin Med Phys. 2016;17:242–253.