Beam Quality Verification Using IC Profiler with Quad Wedge Accessories

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Introduction

The standard approach to beam quality determination is the measurement of depth dose curves using an ion chamber in water. Such measurements require a significant investment of time and resources, and are also prone to errors, both in equipment setup and interpretation of results. Even for constancy checks in solid phantoms, measurements of at least two depths are necessary. Because these depths generally differ depending on beam energy, particularly for electron beams, multiple trips into the vault are required to change the setup.

As an alternative to measurements at different depths, beam quality can be determined in a single measurement if an attenuating object of varying thickness, such as a wedge, is placed into the field. The attenuation of the beam by the object depends on the energy spectrum of the beam. If the relationship between the amount of attenuation (i.e., change in field shape relative to the open field) and beam quality can be established, any variation in beam quality can then be deduced from attenuation changes. This approach is well suited for use with 2D diode or ion chamber arrays, which further simplifies beam quality evaluation and reduces the time needed to complete it.

The use of a wedge-shaped absorber for electron energy constancy checks using radiographic film was first proposed in 1981[1]. Subsequent reports describe energy monitoring with a wedge using an ion chamber[2] and a diode array. [3] & [4] Energy measurements using an IC Profiler ion chamber array with Double Wedge accessory (Sun Nuclear Corporation, Melbourne, FL) are described in the Varian Reference Bulletin. [5] A Double Wedge accessory is designed to place two wedge-shaped aluminum absorbers in the toe-to-toe orientation over one of the two diagonal axes of the IC Profiler.

The goal of this report is to describe the use of IC Profilers with new Quad Wedge accessories for verification of beam quality of photon and electron beams. Quad Wedge accessories include a copper wedge plate for photon beam measurements and an aluminum wedge plate for electron beam measurements. Each wedge plate is constructed similarly to the Double Wedge accessory, except that it contains two wedge pairs – one on each of the diagonal axes. This arrangement is expected to provide better measurement statistics than a single or double wedge.

Equipment and Methods

IC Profiler and Quad Wedge Accessories

The IC Profiler Model 1122 consists of 251 ion chambers arranged in four linear arrays – X (transverse) axis array, Y (radial) axis array, and two diagonal arrays. The active volume of each detector is 0.046 cm3. The spacing between the detectors is 0.5 cm on the principal (X and Y) axes and 0.7 cm on diagonal axes. The detectors span 32 cm on X and Y axes and 45 cm on diagonal axes. More information on the IC Profiler can be obtained from the Reference Guide[6]. Energy verification with Quad Wedge accessories is supported in Profiler software version 3.4.1 and higher.

Quad Wedge plates (Figure 1) consist of four metal (copper or aluminum) wedges fixed in an aluminum frame and mounted on an acrylic plate with 0.3 cm thickness. The edges of the plates are designed to align flush with the edges of an IC Profiler for easy positioning.

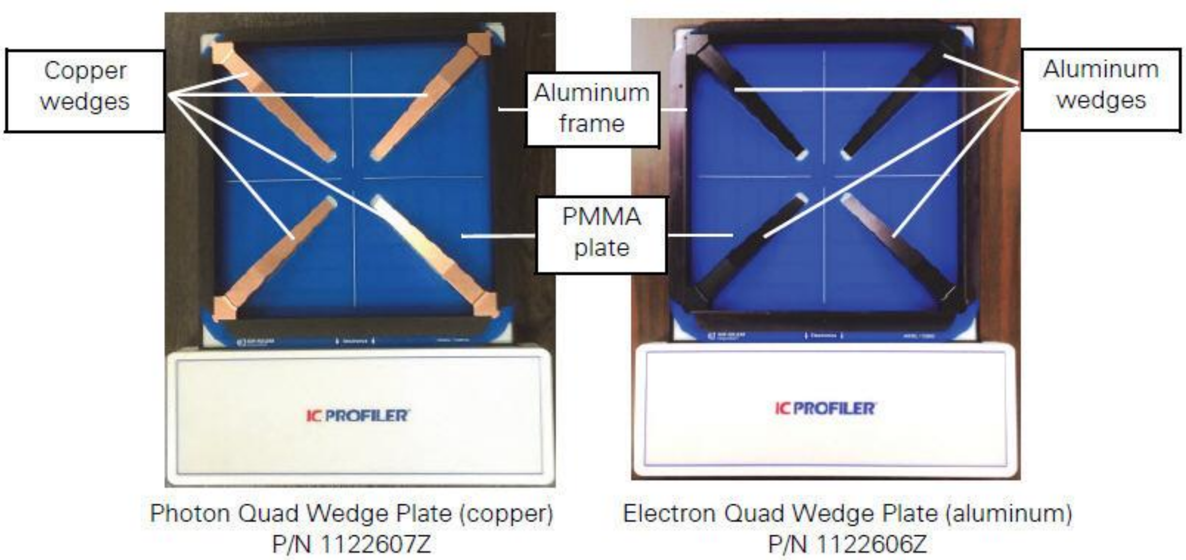

Figure 1: IC Profiler Quad Wedge plate accessories mounted on IC Profiler

The wedges vary the amount of buildup over the positive and negative diagonal axes. The maximum water-equivalent buildup over the detector located under the thickest portion of each wedge, including IC Profiler intrinsic buildup, is 23.9 cm for copper wedges and 8.1 cm for aluminum wedges. Detailed description of Quad Wedge accessories can be found in the Reference Guide[6] and the Technical Bulletin[7].

Data Acquisition

All measurements described in this work were acquired by Varian Medical Systems using TrueBeam accelerators. For photon beams, the measurements and the analysis included the following modes: 2.5 MV (imaging beam), 4, 6, 8, 10, 15, 18, and 20 MV flattened beams, and 6 and 10 MV flattening filter free (FFF) beams. Electron beam modes evaluated were 6, 9, 12, 15, 16, 18, 20, and 22 MeV. All reference to energy in this document is per BJR #11.

Photon Beams Data Acquisition

For photon beams, beam quality was specified in terms of percent depth dose at the depth of 10 cm in water (D10). D10 values were obtained from the depth dose curves measured in a water tank and normalized to maximum dose. For each energy mode (e.g., 6 MV), D10 values were measured at nominal bending magnet currents, as well as in detuned beams, where the beam spectrum was varied by adjusting the bending magnet current several percent above and below the nominal value. Water tank measurements of D10 and IC Profiler measurements with Quad Wedge accessory were acquired for each setting of the bending magnet current.

Water tank measurements were taken under the conditions specified by Varian's Customer Acceptance procedure (TrueBeam / TrueBeam STx Installation Product Acceptance[8]: 100 cm SSD and 10x10 cm2 field size. Beam profiles with Quad Wedge Accessory (Quad Wedge profiles) were measured using the IC Profiler at 100 cm SSD (to the top surface of IC Profiler, before placing the Quad Wedge plate) and using a 30x30 cm2 field. 200 monitor units (MU) were delivered in each measurement. Prior to acquisition, an IC Profiler array calibration was performed for each energy mode at the nominal bending magnet current.

Electron Beams Data Acquisition

Data acquisition methods for electron beams were similar to that for photons, excepting the differences described here. The beam quality for electron beams is reported using the depth at which the dose falls to 50% of its maximum value (R50). Water tank measurements of R50 and Quad Wedge profile measurements were collected at nominal and detuned values of bending magnet current.

IC Profiler measurements were obtained at the SSD of 100 cm using the 25x25 cm2 electron applicator. 200 MU were delivered in each measurement. Water tank R50 measurements were performed at 100 cm SSD using 15x15 cm2 electron applicator per Varian's Installation Product Acceptance procedure[8].

Energy Analysis Using Quad Wedge Accessories

Analysis of Quad Wedge Measurements

When a measurement is taken with the Quad Wedge accessory, relative dose measurements on diagonal axes, normalized to beam central axis, are directly related to the beam fluence that is transmitted through the metal wedge. These relative measurements are referred to in Figure 2 as Normalized Dose. With increasing energy, fluence transmitted through the wedge is increased, and therefore the relative measurements on the diagonal axes are expected to increase. Similarly, the relative measurement under the wedge is expected to decrease if beam energy decreases. However, Figure 2(a) shows that this is not the case: the red line, indicating increased bending magnet current, is actually below the black line, which represents nominal bending magnet current, giving the impression of lower energy. The same discrepancy occurs with decreased bending magnet current, represented by the blue line. This phenomenon is explained by the fact that an increase in energy due to bending magnet detuning is accompanied by a decrease in fluence relative to the central axis, and vice versa. This is evident from the X axis profiles, which are not attenuated by the wedge as can be seen in Figure 2(b). A similar change in off-axis profiles with bending magnet current has been discussed in other published works[9]&[10].

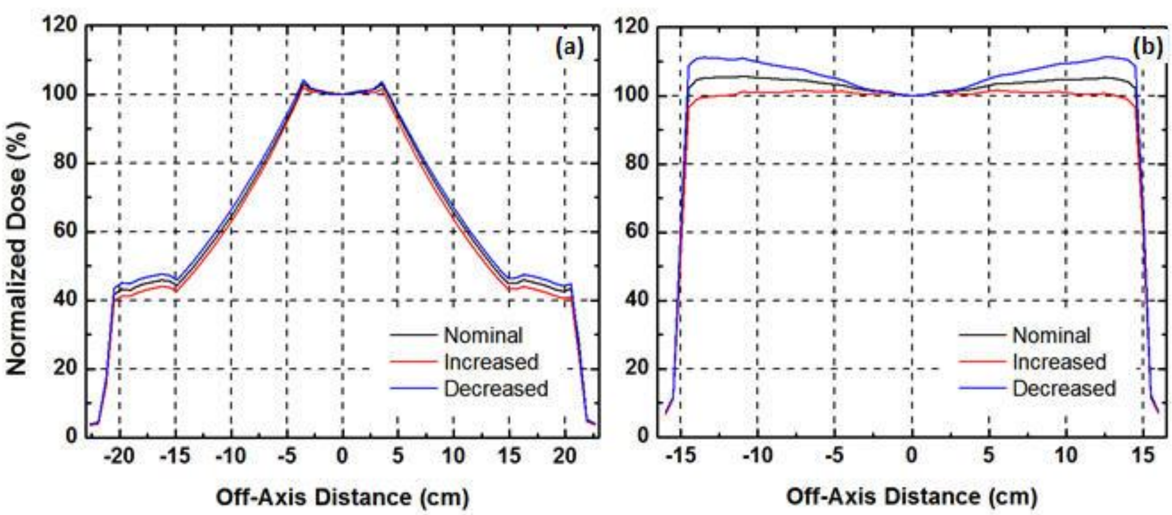

Figure 2: Quad Wedge profiles along positive diagonal axis (a) and X axis (b) for 6 MV beam with different bending magnet currents: nominal (black line), increased by 10% of nominal (red line), and decrease by 10% of nominal (blue line).

The off-axis dose changes are a manifestation of the angular distribution of bremsstrahlung fluence as a function of electron beam energy: as the energy of the electron beam impinging on the target increases, the bremsstrahlung spatial distribution becomes increasingly more forward-peaked[11]. This phenomenon is the rationale behind another method of energy verification, which is based on monitoring of the magnitude of "horns" in flattened beams at the depth of maximum dose[9], [12]. While this method is suitable for energy constancy monitoring, it does not provide a direct correlation to a beam quality metric, e.g., a beam profile for a properly tuned, flattened 6MV mode is barely distinguishable from the same profile for 10 MV mode (Figure 3(a)). On the other hand, Quad Wedge measurements, or, for that matter, other types of measurements based on attenuation, are directly dependent on the penetrating power of the beam (Figure 3(b)).

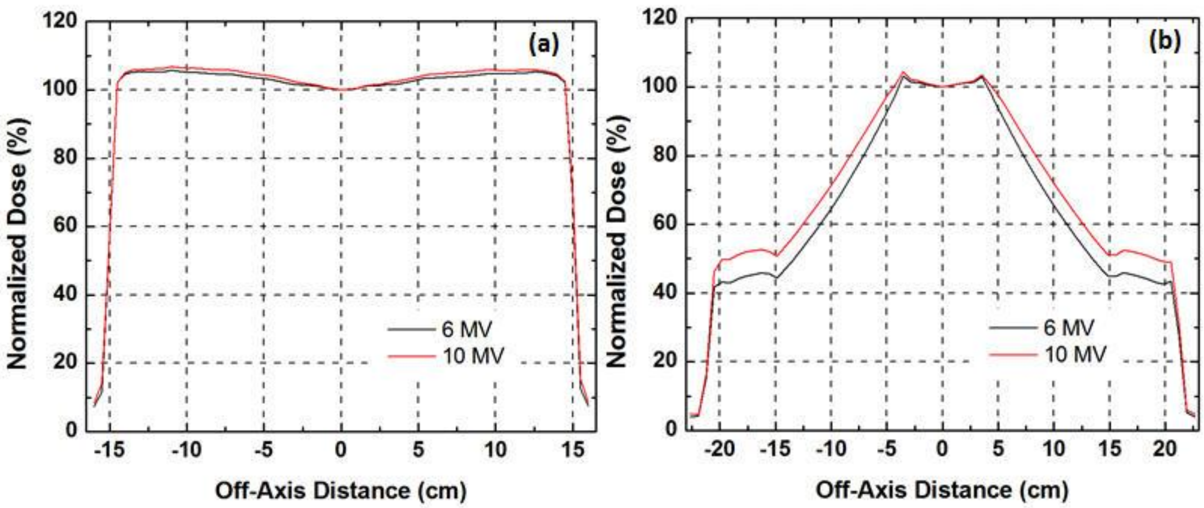

Figure 3. Comparison of 6 MV and 10 MV beam profiles for X axis (a) and positive diagonal axis with the Quad Wedge accessory (b).

In the case of Quad Wedge measurements at varying bending magnet currents, the two competing effects – higher transmission through the wedge and lower fluence, or vice versa – work against each other to produce a very weak and irreproducible correlation between profile area and energy. It is evident from Figure 2(a) that the change in the Quad Wedge profiles is small and is in the direction opposite to what would be expected given the change in beam energy. Therefore, using data only from diagonal axes is not sufficient for accurate energy analysis, and the change in fluence must be taken into account.

The effect of fluence change can be "factored out" if the diagonal profile areas are normalized by the principal profile areas yielding the parameter AreaRatio:

$$AreaRatio = \frac{PDArea+NDArea}{XArea+YArea} \quad (1)$$

where PDArea, NDArea, XArea, and YArea represent the sum of dose readings from a subset of detectors for positive diagonal, negative diagonal, X, and Y axes, respectively. (The details on the detector range included in this calculation are discussed with the next equation.) Thus, AreaRatio is directly related to the transmission through the wedge.

For electron beams, the change of field profile shape with energy is much less pronounced, but is nonetheless present. Therefore, the same approach was applied to the processing of Aluminum Quad Wedge measurements in electron beams.

The areas for each array axis are calculated as the sum of readings from a subset of detectors on that axis:

$$Area_{ax} = \sum_i D_{i,ax} \qquad (2)$$

D refers to corrected counts (detector readings corrected for leakage and array sensitivity factors) for detector i, subscript ax indicates the axis – X, Y, positive diagonal (PD), or negative diagonal (ND). The index i limits the detector range included in the calculation only to the detectors that are within a certain distance from the center of the array. Detectors located outside the field and near the toe of a wedge are excluded to avoid errors that may result from uncertainties in positioning of the IC Profiler or Quad Wedge accessories. For photon beams, only detectors that fall between 4.0 cm and 14.0 cm from the array central detector were included for all four array axes. For electron beams, this range was 4.0 cm to 12.0 cm, reflecting the smaller field size used for electron Quad Wedge measurements.[1] *

Correlation of Quad Wedge Profiles with Beam Quality Metrics

The relative change in AreaRatio with bending magnet current is shown in Figure 4(a) for all analyzed photon modes. The change appears to be linear and does not exhibit a marked dependence on the energy mode, including flattening filter free (FFF) modes. For electron beams, as shown in Figure 4(b), the change in AreaRatio also appears to be linear but is clearly dependent on the energy mode.

The relationship between AreaRatio and D10 as determined from the water tank measurements is shown in Figure 5: D10 measured in a water phantom versus AreaRatio.Figure 5. Note that the AreaRatio values shown in Figure 5 and in Figure 4 were derived from the same IC Profiler measurement dataset. AreaRatio increases continuously with D10 across all flattened photon modes; however, there does not appear to be any clear functional dependence that would connect D10 and AreaRatio across all modes. Therefore, a

[1] It should be noted that the analysis of Quad Wedge electron beam measurements in Profiler software differs from that of the measurements taken with the Sun Nuclear's Double Wedge accessory. For more information on the Double Wedge accessory and its use for electron beam energy analysis see Ref. 6 and 7.

linear fit was applied to each energy mode to establish the correlation between the two parameters. An example of the linear dependence is shown in the inset of Figure 4 for 10 MV mode. The down shift from flattened (FF) modes to FFF modes is due to the shape of the beam profile: because the fluence is higher in the middle, where the thickness of the wedge, and hence the attenuation, is smaller, the ratio of the profiles with and without the wedge (i.e., AreaRatio parameter) is larger.

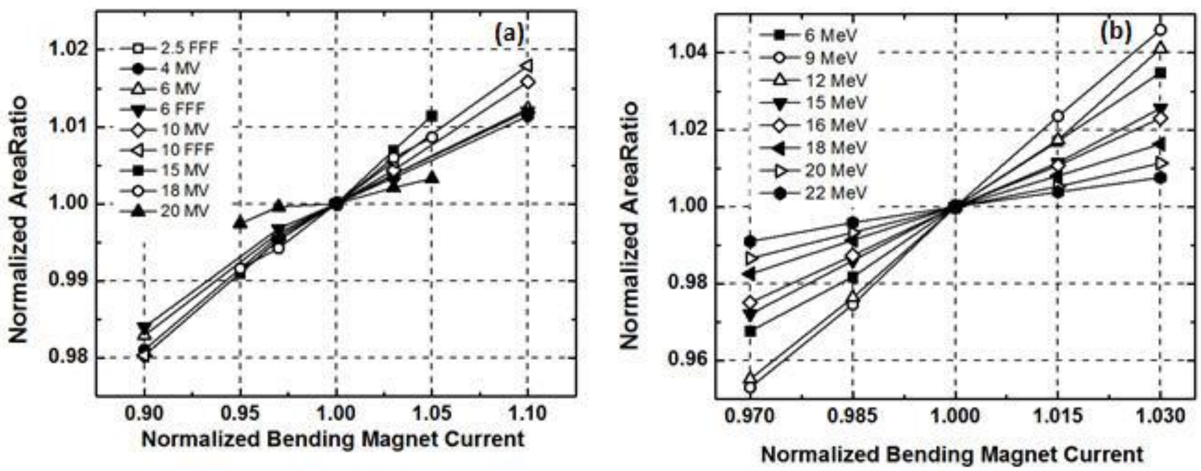

Figure 4: Relative change in AreaRatio as a function of bending magnet current for photon (a) and electron beams (b). The lines are drawn as a guide for the eye and do not represent a linear fit.

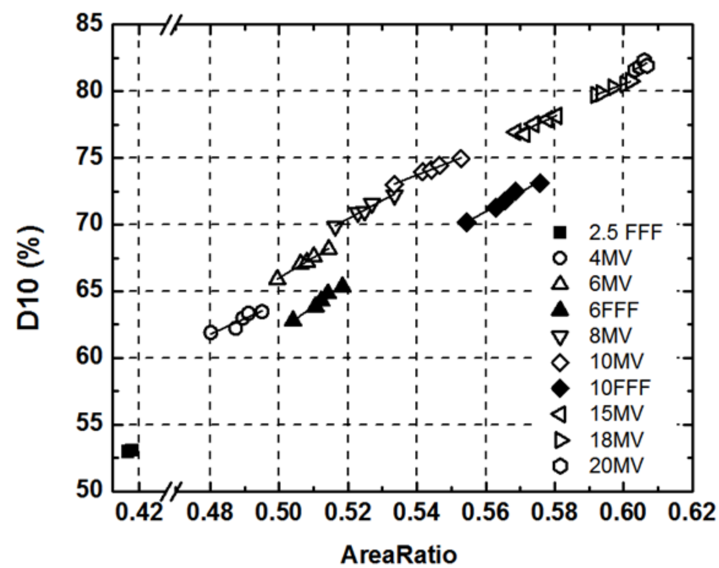

Figure 5: D10 measured in a water phantom versus AreaRatio.

The correlation between R50 and AreaRatio is shown in Figure 6. For each energy mode, it is well represented by a second-order polynomial fit. An example of this is provided in the inset of Figure 6 for 9 MeV beam.

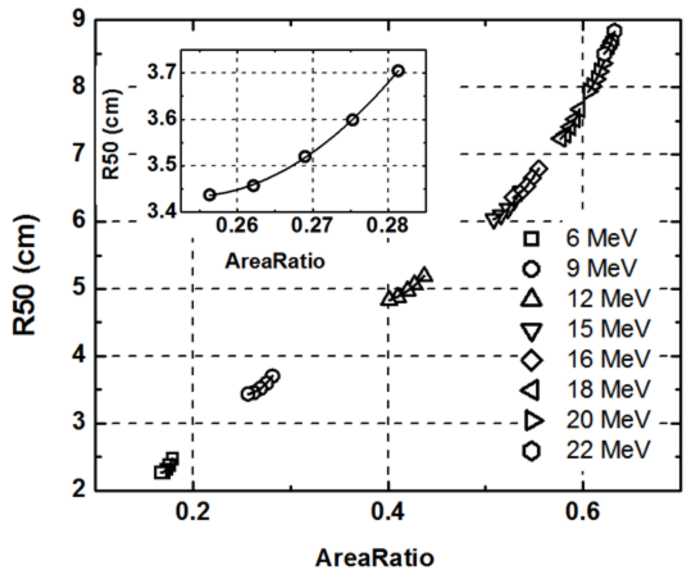

Figure 6: Electron beam R50 measured in water phantom versus AreaRatio for all electron energy modes and the quadratic fits. Inset: Quadratic relationship between R50 and AreaRatio for 9 MeV beam.

Test Results

The coefficients of linear and quadratic fits described in the previous sections allow calculation of D10 or R50 values using only AreaRatio values from IC Profiler Quad Wedge measurements. This approach was validated on 11 new linac installations, which were the pilot sites for Varian's IC Profiler project. The data acquisition at pilot sites included IC Profiler Quad Wedge measurements, as well as water tank measurements. The same IC Profiler and Quad Wedge accessory were used for each measurement. For each available energy mode of each pilot site linac, the D10 or R50 value was calculated from IC Profiler measurement using the known relationships between AreaRatio and D10 or R50, and the results were compared to water tank data. Total number of evaluated energy modes was 84 for photon beams and 68 for electron beams. The number of measurements on different linacs in each energy mode is provided in *Table 1*.

The root-mean-square (RMS) difference across all energy modes between beam quality metrics measured in a water tank and calculated from Quad Wedge measurements was 0.21% for photon beam D10 and 0.017 cm for electron beam R50. The RMS errors for individual modes are provided in *Table 1*. Standard deviation in D10 and R50 errors was 0.15% and 0.018 cm, respectively. Contrasting these values against the typical Varian tolerances for D10 and R50, which are 1% and 0.1 cm, respectively, it can be concluded that the accuracy of this method is suitable for beam quality verification.

Because the models use the actual value of AreaRatio, errors can occur if the dimensions of a given Quad Wedge accessory are significantly different from the hardware used to create the models. To determine how manufacturing tolerances affect AreaRatio and hence the uncertainty in D10, measurements with 41 Quad Wedge plates were performed using the same IC Profiler under the same 6 MV beam. The standard deviation in D10 was 0.13%.

PHOTON BEAMS		
ENERGY MODE (MV)	NUMBER OF SAMPLES	RMS ERROR (%)
2.5	7	0.38
4	3	0.17
6	14	0.25
8	2	0.10
10	14	0.10
15	12	0.18
18	5	0.09
20	3	0.16
6 FFF	12	0.24
10 FFF	12	0.15

ELECTRON BEAMS		
ENERGY MODE (MV)	NUMBER OF SAMPLES	RMS ERROR (%)
6	12	0.010
9	12	0.018
12	12	0.011
15	9	0.013
16	6	0.025
18	8	0.012
20	6	0.024
22	3	0.030

Table 1: Root-mean-square (RMS) difference between calculated and measured beam quality metrics

IC Profiler Measurement Reproducibility

The energy resolution of Quad Wedge measurements depends on their reproducibility, if all the other variables (Quad Wedge hardware, IC Profiler, array calibration, beam, etc.) are held constant. To simulate repeated IC Profiler measurements, a random error was computationally introduced into the measured data, and the measured data were reprocessed to calculate AreaRatio and D10 or R50. Randomly generated error values were normally distributed about zero, with the standard deviation of 0.2%, which is a conservative estimate of IC Profiler measurement reproducibility. The error was applied to the corrected detector measurements - the output of IC Profiler measurement used for AreaRatio calculation. The process was repeated 100 times, simulating 100 reproducibility measurements for each photon and electron mode. The standard deviations of D10 and R50 values are provided in Table 2. The results suggest that the reproducibility of Quad Wedge energy verification results (3 standard deviations) is 0.1% for D10 and 0.03 cm for R50.

PHOTON BEAMS	
ENERGY MODE (MV)	D10 STANDARD DEVIATION (%)
2.5	0.009
4	0.020
6	0.028
8	0.028
10	0.018
15	0.023
18	0.019
20	0.034
6 FFF	0.033
10 FFF	0.031

ELECTRON BEAMS	
ENERGY MODE (MeV)	R50 STANDARD DEVIATION (cm)
6	0.0014
9	0.0013
12	0.0018
15	0.0032
16	0.0043
18	0.0050
20	0.0064
22	0.0086

Table 2: Root-mean-square (RMS) difference between calculated and measured beam quality metrics

Conclusion

Energy verification using IC Profiler with Quad Wedge accessories can yield results with accuracy comparable to water tank measurements. For Varian TrueBeam accelerators, the accuracy (3 standard deviations) of calculated D10 and R50 metrics was shown to be 0.45% and 0.05 cm, respectively. The reproducibility of results (3 standard deviations) is 0.1% for D10 and 0.03 cm for R50.

The setup of an IC Profiler and accessories is much simpler than the setup of a water scanning system. This means that the IC Profiler is less prone to errors and uncertainties, which provides more consistent reproducible results. Another advantage of using an IC Profiler rather than a water scanning system for energy verification is a considerable savings of resources and the time it takes to collect actual beam data which increases overall efficiency. This means that initial verification can be done in a shorter period of time. Also, periodic beam quality assurance verification can be performed more frequently with less time and effort. Overall, the IC Profiler with Quad Wedge accessories provides an incremental improvement over traditional methods using the portable water phantom for beam quality verification.

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Customer Documentation

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