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Comparison of the recommendations of the AAPM TG-51 and TG-51 addendum reference dosimetry protocols

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Abstract

This work quantified differences between recommendations of the TG-51 and TG-51 addendum reference dosimetry protocols. Reference dosimetry was performed for flattened photon beams with nominal energies of 6, 10, 15, and 23 MV, as well as flattening-filter free (FFF) beam energies of 6 and 10 MV, following the recommendations of both the TG-51 and TG-51 addendum protocols using both a Farmer® ionization chamber and a scanning ionization chamber with calibration coefficients traceable to absorbed dose-to-water (D_w) standards. Differences in D_w determined by the two protocols were 0.1%–0.3% for beam energies with a flattening filter, and up to 0.2% and 0.8% for FFF beams measured with the scanning and Farmer® ionization chambers, respectively, due to k_Q determination, volume-averaging correction, and collimator jaw setting. Combined uncertainty was between 0.91% and 1.2% ($k = 1$), varying by protocol and detector.

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KEY WORDS
photon beam reference dosimetry, TG-51 addendum

1 | INTRODUCTION

In 1999 the AAPM Task Group 51 report (TG-51) was published, establishing an D_w-based protocol for clinical reference dosimetry of photon and electron beams in place of the previously recommended air kerma-based protocol.[1] According to IROC Houston, 99.8% of North American institutions with compliant machines have implemented TG-51 for clinical reference dosimetry.[2] To address advances since the publication of TG-51, the AAPM published an addendum to this report (TG-51 addendum) in 2014.[3] TG-51 addendum updates k_Q values using Monte Carlo simulations, revises recommendations regarding the use of a lead foil for the determination of k_Q values to address FFF beams and reduce the potential for error, introduces correction factors to account for averaging of the detector signal over the sensitive volume of the ionization chamber (P_{rp}) and contributions from leakage current (P_{leak}), and recommends best practices for protocol implementation to minimize uncertainty. Papageorgiou et al.[4] found that the updates to the k_Q values had an insignificant impact on accelerator output, but did not address the remaining updates in TG-51 addendum. In the current work, accelerator output determined following TG-51 and TG-51 addendum using both a 0.6 cm³ PTW N30013 Farmer® ionization chamber (Freiburg, Germany) and a 0.053 cm³ Exradin A1SL scanning ionization chamber (Standard Imaging, Inc., Middleton, WI, USA) was compared.

2 | METHODS

Reference dosimetry for photon beams with nominal energies of 6 MV (6X, 6X-SRS, 6XFFF), 10 MV (10X, 10XFFF), 15 MV (15X),

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Abbreviation: D_w, absorbed dose-to-water; FFF, flattening-filter free; P_{leak}, leakage ionization correction; P_{rp}, volume-averaging correction; TG-51, Task Group 51 report; TG-51 addendum, addendum to Task Group 51 report

and 23 MV (23X) was performed following the recommendations of TG-51 and TG-51 addendum. The 6XFFF and 10XFFF energies do not have flattening filters, and the 6X-SRS energy has a thin filter capable of flattening fields up to 15×15 cm^2. Measurements of the 6X-SRS and 23X energies were completed on a Trilogy® linear accelerator (Varian Medical Systems, Inc., Palo Alto, CA, USA), while measurements of the remaining energies were completed on a Varian TrueBeam™ STx linear accelerator. A 0.6 cm^3 PTW N30013 Farmer® ionization chamber and a 0.053 cm^3 Exradin A1SL scanning ionization chamber, both with ADCL $N_{D,w}$ calibration coefficients, were used with an ADCL-calibrated PTW UNIDOS electrometer for measurements in a Blue Phantom 3D scanning water tank (IBA Dosimetry, Schwarzenbruck, Germany). PDD, inline, and crossline profiles were measured with a 0.13 cm^3 IBA CC13 scanning ionization chamber.

Prior to measurements, ionization chambers were allowed to thermally equilibrate with the water for 30 min. A bias voltage of -300 V was applied to the ionization chamber, and a dose of 10 Gy was delivered to the ionization chamber to stabilize the measured ionization current. The leakage current was then nullified. Following each change in bias voltage, a dose of 10 Gy was delivered to the ionization chamber to stabilize the measured ionization current. Reference dose measurements were completed at a SAD of 100 cm using a vertical beam orientation. Five consecutive measurements of 100 MU were averaged for each measurement of raw ionization. The two-voltage technique was used to determine the recombination correction with bias voltages of -300 V and -100 V. As discussed in Section 3, the validity of the two-voltage technique was verified with measurements of Jaffé plots.

In this work the TG-51 procedure used a lead foil for $\%dd(10)_x$ measurements for energies greater than 10 MV (i.e., 15 MV and 23 MV), determined k_Q from $\%dd(10)_x$ using data for the PTW N30001 and Exradin A1 ionization chambers from table 1 of Ref. [1], and set the collimator jaws to a 10×10 cm^2 field according to the digital readout. Conversely, the TG-51 addendum procedure in this work used a lead foil for $\%dd(10)_x$ measurements for the FFF beams, used the interim measure (i.e., Eq. 15 of Ref. [1]) to calculate $\%dd(10)_x$ for energies greater than 10 MV, determined k_Q from $\%dd(10)_x$ using Table 1 of Ref. [3], set the collimator jaws to define a 10×10 cm^2 radiation field, and applied P_{leak} and P_{rp} corrections to the raw ionization reading. The fluence incident on the ionization chamber, and therefore the total ionization produced within the chamber, is dependent on the size of the radiation field. Consequently, deviation from the specified 10×10 cm^2 field size introduces measurement uncertainty, which TG-51 addendum emphasizes must be considered. The collimator jaw settings for a 10×10 cm^2 radiation field in the TG-51 addendum procedure were determined by measurement of the full width at half maximum of inline and crossline profile scans with the CC13 ionization chamber. Between each adjustment of the collimator position, the jaws were first programmed to a 15×15 cm^2 field to prevent hysteresis and minimize mechanical slop. P_{leak} was determined using a one-minute integration of ionization current in the absence of a radiation field

with a bias voltage of -300 V applied to the ionization chamber. P_{rp} was determined as the product of $k_{vol,in}$ and $k_{vol,cr}$:

$$k_{vol,in} = \frac{\iint_A w(0,y)dy}{\iint_A w(0,y)OAR(0,y)dy}, k_{vol,cr} = \frac{\iint_A w(x,0)dx}{\iint_A w(x,0)OAR(x,0)dx} \quad (1)$$

where $OAR(x,y)$ is the inline (y)/crossline (x) profile normalized to the central axis, and

$$w(x,y) = \sqrt{R^2 - x^2} \quad (2)$$

where R is the radius of the collecting volume.

3 | RESULTS AND DISCUSSION

Comparisons of reference dosimetry following the recommendations of TG-51 and TG-51 addendum using the PTW N30013 and Exradin A1SL ionization chambers are shown in Tables 1 and 2, respectively. The parameters not shown in these tables, namely P_{ion}, P_{pol}, P_{elec}, and P_{TP}, are identical between the two protocols. For the Exradin A1SL ionization chamber, differences in D_w/MU between the two protocols ranged between 0.1% and 0.3%. For the PTW N30013 ionization chamber, differences in D_w/MU ranged between 0.1% and 0.2% for beam energies with a flattening filter, and 0.5% and 0.8% for FFF beam energies.

Differences in the output determined using the two protocols were due to k_Q determination, use of the P_{rp} correction, and collimator jaw setting. The ratios of k_Q determined using the two protocols for the PTW N30013 and Exradin A1SL ionization chambers ranged from 0.999–1.002 and 0.996–0.999, respectively. TG-51 addendum states that differences of up to 0.5% were found between the new and original k_Q values.[3] Furthermore, the ionization chambers used in this work were not included in TG-51, which can result in a k_Q assignment uncertainty of up to 0.5%.[3] Therefore, the differences in k_Q between the two protocols observed in this work are within expected variations for ionization chambers that were not listed in TG-51. For the smaller-volume Exradin A1SL chamber, P_{rp} did not exceed 0.1%, while P_{rp} values of up to 0.4% and 0.6% were measured for beam energies with and without a flattening filter, respectively, for the PTW N30013 chamber. For comparison, Kry et al.[5] determined that a volume-averaging correction of 0.2% was necessary for measurements of 6XFFF and 10XFFF beam energies from a TrueBeam™ accelerator using a Farmer-type chamber. Whereas P_{rp} was determined by averaging over inline and crossline dose profile scans in the current work, Kry et al.[5] used a 1D average over an inline dose profile measured using film. The difference between a 1D and 2D average to determine P_{rp} is minimal; in the current work, the largest correction from averaging over the crossline profile was less than 0.05%. The digital readout for a 10×10 cm^2 radiation field is shown in Table 1 for each beam energy. Measured ionization differed up to 0.2% and 0.3% between 10×10 cm^2 fields defined according to the digital readout (i.e., TG-51 procedure) or dose profile scans (i.e., TG-51 addendum procedure) for the PTW N30013 and Exradin A1SL chambers, respectively.

TABLE 1 PTW N30013 Farmer® ionization chamber results.

Energy	6X	6X-SRS	10X	15X	23X	6XFFF	10XFFF
$(D_w/MU)_{TG51}^{addendum}$	1.001	0.999	1.002	0.999	1.001	1.005	1.008
$(k_Q)_{TG51}^{addendum}$	1.000	1.001	1.001	1.002	1.002	0.999	1.000
P_{rp}	1.000	0.998	1.001	0.996	0.999	1.004	1.006
$(M_{raw})_{TG51}^{addendum}$	1.001	1.000	1.001	1.001	1.000	1.002	1.002
Digital readout for 10×10 cm^2 radiation field	9.9×10.2	9.9×10.0	10.0×10.2	9.9×10.2	9.9×10.0	10.0×10.3	10.1×10.4

TABLE 2 Exradin A1SL scanning ionization chamber results.

Energy	6X	6X-SRS	10X	15X	23X	6XFFF	10XFFF
$(D_w/MU)_{TG51}^{addendum}$	0.999	0.997	0.998	0.998	0.999	1.001	0.998
$(k_Q)_{TG51}^{addendum}$	0.998	0.998	0.996	0.998	0.999	0.998	0.996
P_{rp}	1.000	1.000	1.000	0.999	1.000	1.001	1.000
$(M_{raw})_{TG51}^{addendum}$	1.002	0.999	1.001	1.001	1.001	1.002	1.003

TABLE 3 Percentage difference in D_w/MU measured with each ionization chamber.

Energy	6X	6X-SRS	10X	15X	23X	6XFFF	10XFFF
TG-51	0.50	0.03	0.47	0.11	0.13	0.57	0.80
TG-51 addendum	0.40	0.11	0.22	0.06	0.19	0.38	0.28

Differences in D_w/MU measured with the two ionization chambers following a given reference dosimetry protocol are shown in Table 3. Differences of up to 0.80% between the PTW N30013 and Exradin A1SL ionization chambers were observed for TG-51, while the largest difference for TG-51 addendum was 0.40%. As discussed below, these differences are all within the estimated measurement uncertainty ($k = 1$).

Uncertainty estimates for both reference dosimetry protocols performed with each ionization chamber are shown in Table 4 as percent standard uncertainties. The combined uncertainty estimate assumes that all uncertainties are uncorrelated. The SSD for both protocols was measured using the front pointer with an estimated uncertainty of 0.5 mm. The methodology from AAPM Task Group 106 was used to define the water surface with an estimated uncertainty of 0.5 mm.[6] Based on the constancy of repeated profile measurements, an uncertainty of 0.5 mm in the field size setting was assumed for TG-51 addendum, while an uncertainty of 4 mm was assumed for TG-51 based on established tolerances for jaw positioning.[7] The uncertainties in Table 4 are based on measured differences in ionization due to the estimated jaw positioning uncertainty. Uncertainty in the temperature-pressure correction was determined based on observed variations in the temperature and pressure of 0.5°C and 0.33 kPa, respectively, over the course of measurements. No consideration was made for humidity, so the uncertainty from Table 4 was assumed based on a humidity range of 20%–80%. The uncertainty in charge measurement is based on maximum differences between repeated ionization measurements with an applied bias of −300 V, with a change in bias voltage between measurements.

TABLE 4 Uncertainty budget with all values given as percent standard uncertainties.

Parameter	TG-51		TG-51 addendum	
	N30013	A1SL	N30013	A1SL
SSD setting	0.10	0.10	0.10	0.10
Depth setting	0.25	0.25	0.25	0.25
Field-size setting	0.20	0.20	0.05	0.05
Charge measurement	0.10	0.30	0.10	0.30
P_{TP} correction	0.18	0.18	0.18	0.18
Humidity	0.15	0.15	0.15	0.15
^{60}Co $N_{D,w}$	0.65	0.65	0.65	0.65
k_Q factor	0.50	0.50	0.40	0.40
Assignment of k_Q factor	0.50	0.50	0.20	0.20
Stability of reference chamber	0.10	0.10	0.10	0.10
P_{pol}	0.10	0.30	0.10	0.30
P_{ion}	0.10	0.10	0.10	0.10
Pre-irradiation history	0.10	0.10	0.10	0.10
Leakage current	0.10	0.10	0.10	0.10
Linac stability	0.05	0.05	0.05	0.05
P_{elec}	0.10	0.10	0.10	0.10
P_{rp}	0.60	0.10	0.10	0.10
Combined ($k = 1$)	1.2	1.2	0.91	0.99

Monthly intercomparisons between the reference ionization chambers and a third reference-class ionization chamber indicated stability of the detectors within ±0.1%. A dose of 10 Gy was delivered to each ionization chamber after changes in applied bias, limiting the short-term drift in ionization chamber response to less than 0.1%.[8] Following nullification of the leakage current, the measured leakage over a one-minute integration in the absence of radiation was 0 fC; therefore, no correction was applied for leakage, and an uncertainty of 0.1% was assumed. Measurements of Jaffé plots following the

methodology of McEwen[8] verified the accuracy of the two-voltage technique for the determination of P_{ion} within 0.1%. The uncertainty in the polarity correction was determined from the uncertainty in charge measurement. The uncertainty in the linac stability was taken as 0.05%.[3] Based on the repeatability of profiles measured with different detectors, the uncertainty in P_{rp} was estimated as 0.1% for TG-51 addendum. For TG-51, which does not recommend the use of a volume-averaging correction, the uncertainty estimates are based on the maximum P_{rp} values determined with TG-51 addendum. The uncertainty in the k_Q factor was taken as 0.4% and 0.5% for TG-51 addendum and TG-51,[3] respectively. The ionization chambers used in this work are not listed in TG-51, so an uncertainty of 0.5% in the assignment of k_Q was estimated based on the use of k_Q values for chambers with similar construction.[1] The use of the interim method for k_Q determination of energies greater than 10 MV in the TG-51 addendum procedure contributes a k_Q assignment uncertainty of 0.2%.[3] As shown in Table 4, the combined uncertainty ($k = 1$) is 0.2% to 0.3% lower when following TG-51 addendum, due primarily to improved accuracy in k_Q assignment, use of a volume-averaging correction, and verification of the field-size setting.

Procedurally, the greatest difference between the two protocols is the measurement of inline and crossline dose profiles to correct for dose averaging over the volume of the ionization chamber, which may require a different water phantom than is normally used. Additionally, if profile scanning is used to measure the inline and crossline dose profiles, then a scanning ionization chamber should be used. To avoid the need to setup multiple detectors, adopters of TG-51 addendum may prefer to use a reference-class scanning ionization chamber, such as the Exradin A1SL chamber employed in this work, to perform reference dosimetry. However, as stated in TG-51 addendum, only reference-class ionization chambers should be used for reference dosimetry. Apart from the measurement of inline and crossline dose profiles, the implementation of TG-51 addendum requires only the use of different reference data (i.e., k_Q determination) and adjustments to existing procedures (i.e., use of a lead foil). For institutions that employ in-house spreadsheets for the calculation of D_w/MU from the data collected during reference dosimetry, the necessary changes to these spreadsheets for the implementation of TG-51 addendum should be carefully verified. During the initial implementation of TG-51 addendum, reference dosimetry should be completed following both protocols to quantify the impact the change in reference dosimetry protocol will have on dosimetric output. Although the expected change in output is less than 1% as shown in this work, physicians should be notified of the change since the dose delivered to patients will be impacted.

4 | CONCLUSIONS

In this work differences between the TG-51 and TG-51 addendum reference dosimetry protocols were quantified. Differences of up to 0.8% in the D_w/MU were measured between the protocols, with a measurement uncertainty of 0.91%–1.2% ($k = 1$). For reference dosimetry of FFF beam energies with a 0.6 cc Farmer-type ionization chamber, volume-averaging corrections of up to 0.6% were measured. Failure to verify the dimensions of the radiation field resulted in measurement differences of up to 0.3%.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Almond PR, Biggs PJ, Coursey BM, et al. AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams. *Med Phys*. 1999;26:1847–1870.
2. Lowenstein J. Personal communication. March 28, 2017.
3. McEwen M, DeWerd L, Ibbott G, et al. Addendum to the AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon beams. *Med Phys*. 2014;41:041501.
4. Papageorgiou S, Georgolopoulou P, Nikoletopoulos S, Laskaratos G, Xenofos S. Implementation of the new TG-51 addendum in clinical practice. *Phys Med*. 2014;30:e115.
5. Kry SF, Popple R, Molineu A, Followill DS. Ion recombination correction factors (P_{ion}) for Varian TrueBeam high-dose-rate therapy beams. *J Appl Clin Med Phys*. 2012;13:318–325.
6. Das IJ, Cheng CW, Watts RJ, et al. Accelerator beam data commissioning equipment and procedures: report of the TG-106 of the Therapy Physics Committee of the AAPM. *Med Phys*. 2008;35:4186–4215.
7. Klein EE, Hanley J, Bayouth J, et al. Task Group 142 report: quality assurance of medical accelerators. *Med Phys*. 2009;36:4197–4212.
8. McEwen MR. Measurement of ionization chamber absorbed dose k_Q factors in megavoltage photon beams. *Med Phys*. 2010;37:2179–2193.