A Monte Carlo derived TG-51 equivalent calibration for helical tomotherapy

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Helical tomotherapy (HT) requires a method of accurately determining the absorbed dose under reference conditions. In the AAPM's TG-51 external beam dosimetry protocol, the quality conversion factor, k_Q, is presented as a function of the photon component of the percentage depth-dose at 10 cm depth, $\%\mathrm{dd}(10)_x$, measured under the reference conditions of a $10\times 10\ \mathrm{cm}^2$ field size and a source-to-surface distance (SSD) of 100 cm. The value of $\%\mathrm{dd}(10)_x$ from HT cannot be used for the determination of k_Q because the design of the HT does not meet the following TG-51 reference conditions: (i) the field size and the practical SSD required by TG-51 are not obtainable and (ii) the absence of the flattening filter changes the beam quality thus affecting some components of k_Q. The stopping power ratio is not affected because of its direct relationship to $\%\mathrm{dd}(10)_x$. We derive a relationship for the Exradin A1SL ion chamber converting the $\%\mathrm{dd}(10)_x$ measured under HT "reference conditions" of SSD=85 cm and a $5\times 10\ \mathrm{cm}^2$ field-size $[\%\mathrm{dd}(10)_{x[\mathrm{HT\ Ref}]}]$, to the dosimetric equivalent value under for TG-51 reference conditions $[\%\mathrm{dd}(10)_{x[\mathrm{HT\ TG\text{-}51}]}]$ for HT. This allows the determination of k_Q under the HT reference conditions. The conversion results in changes of 0.1% in the value of k_Q for our particular unit. The conversion relationship should also apply to other ion chambers with possible errors on the order of 0.1%. © *2005 American Association of Physicists in Medicine*. [DOI: 10.1118/1.1897084]

I. INTRODUCTION

The clinical introduction of helical tomotherapy [TomoTherapy Inc., Madison, WI] (HT)[1] for external beam radiation therapy requires the accurate calibration of absorbed dose per monitor unit of delivered radiation. The recommended procedure for absorbed dose output calibration of conventional linear accelerators in North America is the AAPM's TG-51 protocol, which is based on an ion chamber calibrated in a reference ^{60}Co beam at a standards lab.[2] The TG-51 protocol is expressed by

$$D_w^Q = M k_Q N_{D,w}^{^{60}\mathrm{Co}}, \tag{1}$$

where D_w^Q is the absorbed dose to water from a beam of quality Q at the point of measurement in water, M is the fully corrected electrometer reading,[2] k_Q is the quality conversion factor, and $N_{D,w}^{^{60}\mathrm{Co}}$ is the absorbed dose to water calibration coefficient for a cobalt beam. The quality conversion factor, k_Q, has been calculated and tabulated in the TG-51 protocol as a function of the percent depth dose at 10 cm $[\%\mathrm{dd}(10)_x]$ from the photon component of the beam measured in water at a source-to-surface distance (SSD) of 100 cm for a field size (FS) of $10\times 10\ \mathrm{cm}^2$. Throughout this manuscript this measurement setup is referred to as the TG-51 reference conditions, and $\%\mathrm{dd}(10)_x$ is typically referred to as the beam-quality specifier. The current $\%\mathrm{dd}(10)_x$ lookup-table for k_Q is not suitable for the HT unit because the TG-51 reference conditions are not realized due to the physical design of the HT unit and, to a lesser extent, the differences in beam quality for the same mean incident electron energy impinging on the target.

The physical design of the HT unit imposes a maximum field dimension of 5 cm along the axis of the bore at the standard 85 cm isocenter instead of the 10 cm required in the TG-51 protocol. Furthermore, in HT, the isocenter is at 85 cm, the bore diameter is 85 cm, and the maximum couch-to-isocenter distance is approximately 28.5 cm. It thus becomes impractical to use 100 cm SSD and 10 cm depth for calibration as required by TG-51, because this would leave at most a few centimeters for backscatter.

Furthermore the quality of the beam in the HT unit is different from other medical linear accelerators with similar mean incident electron energies (6 MeV) because of the absence of a flattening filter. The HT unit is inherently designed to deliver intensity modulated radiation therapy (IMRT) treatments using its multileaf collimator (MLC) to modulate the beam. Since the beam can always be modulated it does not use a flattening filter because this would attenuate useful photons and result in prolonged treatment times. The absence of a flattening filter produces some appreciable differences in the beam's photon spectrum compared to conventional medical linear accelerators that employ flattening filters. The ion chamber measured transverse beam profile from the HT unit is significantly different from the cross-plane beam profile from a conventional 6 MV medical linear accelerator [Fig. 1(a)]. The "house" shaped HT profile is due to the unfiltered bremsstrahlung distribution.[3] The Monte Carlo calculated energy spectrum of the HT unit photon beam is quite different from our calculation of the Varian 2100EX (Varian 21EX) conventional 6 MV medical linear accelerator and comprises a larger proportion of low-energy photons [Fig. 1(b)] due to reduced beam hardening resulting from the absence of a flattening filter. The differences in spectrum and the difference in scatter from regions off the central axis result in a depth-dose curve which differs from that of a conventional medical linear accelerator under the same measurement conditions. In this work, a new $\%dd(10)_x$ conversion function is determined for use with the TG-51 protocol which accounts for the differences in both the reference geometry and the beam characteristics of HT.

II. METHODS AND MATERIALS

A. Ion chamber

We used an Exradin A1SL [Standard Imaging, Middleton, WI] waterproof ion chamber with 1.1 mm walls of C552 air-equivalent plastic because its small volume ($0.056\ \mathrm{cm}^3$) minimizes volume averaging which could arise from the nonflat beam profile [Fig. 1(a)]. The Exradin A1SL (A1SL) ion chamber has a cavity diameter of 4.05 mm and a length of 4.4 mm. The central electrode of the ion chamber is also comprised of C552 air equivalent plastic.

B. k_Q

The quality conversion factor, k_Q, which converts a ^{60}Co absorbed dose calibration coefficient into one suitable for the HT unit's beam is given by[4]

$$k_{Q[\mathrm{HT\ TG\text{-}51}]}=\frac{[(\overline{L}/\rho)^{\mathrm{water}}_{\mathrm{air}}P_{\mathrm{wall}}P_{\mathrm{repl}}P_{\mathrm{cel}}]_{\mathrm{HT(SSD=85\ cm,FS=5\times10\ cm^2,depth=10\ cm)}}}{[(\overline{L}/\rho)^{\mathrm{water}}_{\mathrm{air}}P_{\mathrm{wall}}P_{\mathrm{repl}}P_{\mathrm{cel}}]_{^{60}\mathrm{Co(SSD=100\ cm,FS=10\times10\ cm^2,depth=10\ cm)}}},\tag{2}$$

where $(\overline{L}/\rho)^{\mathrm{water}}_{\mathrm{air}}$ is the ratio of mean restricted mass collision stopping power (spr) in water to that in air. P_{wall} is a correction factor that accounts for the presence of the ion chamber wall. P_{repl} is a correction for fluence and gradient perturbations due also to the presence of the ion chamber cavity in the radiation field. In practice, P_{repl} for dose measurements in broad photon beams may be accounted for by using an effective point of measurement. The correction factor P_{repl} is inherently contained in all of our calculations of k_Q. Thus dose determination for the HT unit will not require a shift in the reference position after the initial measurement of $\%dd(10)_x$. P_{cel} is the correction accounting for the presence of the central electrode within the ion chamber. In the case of the A1SL, where the ion chamber central electrode is made of the same material as the ion chamber wall, P_{cel} is accounted for within P_{wall}. The k_Q for the A1SL is not included in the TG-51 document. We have thus calculated k_Q for the A1SL under the TG-51 reference conditions (Fig. 2). The calculations for k_Q were made in the same manner and using the same data sources that are used in TG-51.[4–9]

P_{wall} was determined using[4]

$$P_{\mathrm{wall}}=\frac{1}{(\overline{L}/\rho)^{\mathrm{water}}_{\mathrm{air}}[\alpha(\overline{L}/\rho)^{\mathrm{air}}_{\mathrm{C552}}(\overline{\mu_{\mathrm{en}}}/\rho)^{\mathrm{C552}}_{\mathrm{water}}+(1-\alpha)(\overline{L}/\rho)^{\mathrm{air}}_{\mathrm{water}}]},\tag{3}$$

where $(\overline{L}/\rho)^{\mathrm{air}}_{\mathrm{C552}}$ is the air-to-C552 ratio of mean restricted mass collision stopping powers, α is the fraction of ionization arising from electrons originating in the ion chamber wall, and $(\overline{\mu_{\mathrm{en}}}/\rho)^{\mathrm{C552}}_{\mathrm{water}}$ is the C552-to-water ratio of mean mass energy absorption coefficients.

All values required in the determination of k_Q were modeled for a ^{60}Co unit, a Varian 21EX 6 MV [Varian, Palo Alto, CA] medical linear accelerator as well as an HT unit (Siemens accelerator, proprietary collimator/MLC) at five different mean incident electron energies. In each case, the phase space file of the incident photon beam was determined using the BEAMnrc user code.[10,11] The Varian 21EX 6 MV medical linear accelerator was modeled to test the basic accuracy of the calculations and to ensure the congruence of our methods with those of TG-51. Starting from Eq. (2) the calculation of k_Q for HT is based on

$$k_{Q[\mathrm{HT\ TG\text{-}51}]}=\frac{[(\overline{L}/\rho)^{\mathrm{water}}_{\mathrm{air}}P_{\mathrm{wall}}]_{\mathrm{HT\ Calculated}}}{[(\overline{L}/\rho)^{\mathrm{water}}_{\mathrm{air}}P_{\mathrm{wall}}]_{\mathrm{Varian\ 6\ MV\ Calculated}}}\times k_{Q[\mathrm{TG\text{-}51\ \%dd(10)_x=66.6\%}]}.\tag{4}$$

In Eq. (4), the ratio of our calculated $(\overline{L}/\rho)^{\mathrm{water}}_{\mathrm{air}}P_{\mathrm{wall}}$ is used to scale the TG-51 k_Q calculation of $\%dd(10)_x=66.6\%$ for the Varian 21EX. This allows us to deal with minor discrepancies between our calculations and those of TG-51 by using our results only as a scaling factor for the TG-51 values. Equation (4) follows from Eq. (2) with the assumption that $P_{\mathrm{repl[HT]}}=P_{\mathrm{repl[Varian\ 6\ MV]}}$. This assumption is largely true for the A1SL between the 4 and 6 MV nominal accel-

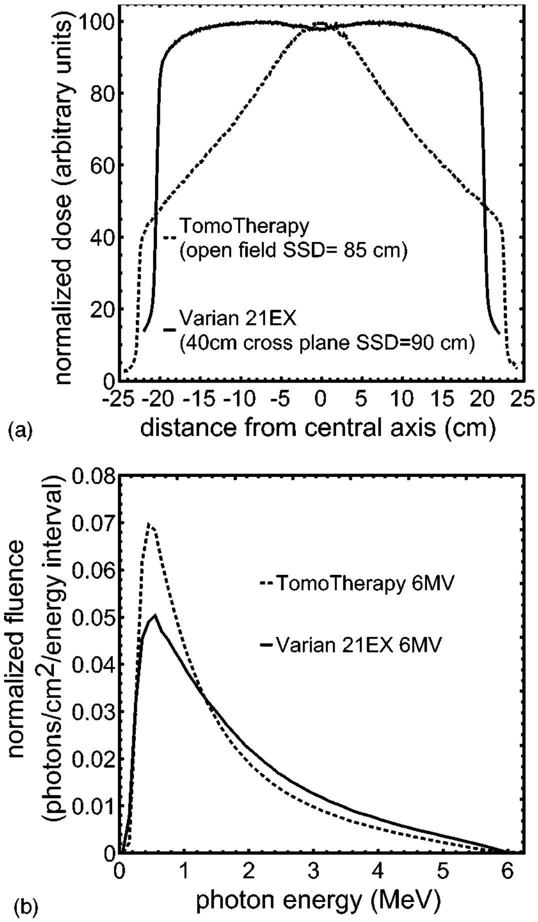

FIG. 1. (a) Measured beam profiles normalized to the maximum absorbed dose for a HT open field at SSD=85 cm and the Varian 21EX in 40-cm-wide cross plane at SSD=90 cm. Both profiles are taken at 10 cm depth. The differences in SSD in the graph are unimportant as this is meant only as a qualitative comparison. (b) Our Monte Carlo calculated energy spectra of the full phase space file for the HT 6.0 MeV mean incident electron energy and the Varian 21EX. Both are scored in air for 5×10 cm^2 field at 85 cm SSD. The fluence was normalized such that the total fluence within the spectrum is equal to 1.

erator potentials[12] as the difference in $P_{\rm repl}$ for a 4-mm-diam chamber between 4 and 6 MV nominal accelerator potentials is only 0.02%.[7] There are indications that $P_{\rm repl}$ may change in very small IMRT beams,[13] but we further assume this is not an issue for the 5×10 cm^2 field used here. Thus the assumption of an invariant $P_{\rm repl}$ will result in a possible maximum error of 0.02% in our values of k_Q for HT. Using Eq. (4) instead of Eq. (2) corrects our data by 0.35% due to the above-listed reasons as well as the inclusion of the $P_{\rm repl}$ correction which we have not calculated independently of Eq. (4). We determine k_Q as a function of the calculated value of $\%{\rm dd}(10)_x$ under our HT reference conditions of a 5×10 cm^2 field at 85 cm SSD $[\%{\rm dd}(10)_{x[\rm HT\ Ref]}]$ for different incident beam energies. The calculated values of k_Q are used to look up the equivalent value of $\%{\rm dd}(10)_{x[\rm HT\ TG\text{-}51]}$ (i.e., the equivalent value for TG-51 reference conditions that would give the same value of k_Q) for each simulated mean

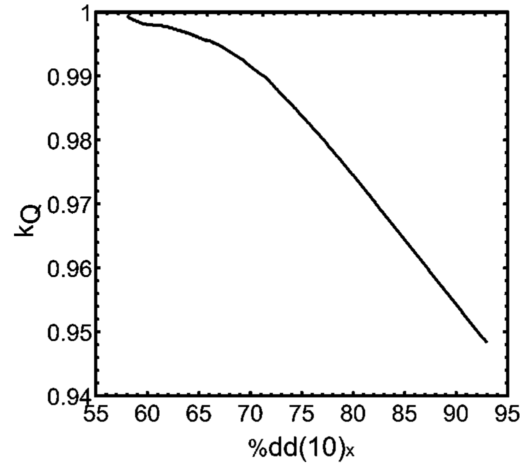

FIG. 2. Values of k_Q for the Exradin A1SL ion chamber as a function of $\%dd(10)_x$ are shown. These values are for conventional medical linear accelerators with a $\%dd(10)_x$ measurement made using the standard TG-51 reference conditions of SSD=100 cm and a 10×10 cm^2 field defined at the surface distance.

incident electron energy of the HT unit. A third-order polynomial is then fit between the values of $\%{\rm dd}(10)_{x[\rm HT\ TG\text{-}51]}$ and $\%{\rm dd}(10)_{x[\rm HT\ Ref]}$.

C. Monte Carlo calculations

1. BEAM modeling parameters

Modeling for all radiation sources was performed using the BEAMNRC user code.[10] The HT unit was modeled for mean incident electron energies of 6.25, 6.0, 5.75, 5.5, and 5.25 MeV. The electron inputs for the HT models used a Gaussian electron energy spread with a full width at half maximum (FWHM) of 12%; this is the same FWHM as used for other Siemens machines.[14] The effect of beam focal spot size on %dd was investigated, but as with conventional linear accelerators, the HT %dd was found to be insensitive to focal spot size.[14] The sensitivity of sprs to focal spot size was also investigated and, as with %dd, were found to be insensitive. The incident electron spatial distribution used for the six bremsstrahlung beams was a radial Gaussian function with a FWHM of 1.41 mm; this FWHM is a typical value.[15–17] Phase space data for the HT unit were generated at 85 cm from the source for a FS of 5×10 cm^2 defined at the surface of the phantom. A Gaussian incident electron energy spread with mean energy of 6 MeV and a 3% FWHM was used for the Varian 21EX model. Phase space data for the Varian 21EX were generated at both 100 cm for a 10×10 cm^2 field and at 85 cm for a 5×10 cm^2 field. The latter scoring was done to investigate the effects of the reference conditions on the variables within k_Q. Range rejection with an ESAVEIN value of 1.5 MeV was used everywhere except for the target where an ESAVEIN value of 0.7 MeV was used.[11] Selective bremsstrahlung splitting was also used for variance reduction.[18] For the ^{60}Co unit, a point source was used with the ^{60}Co energy spectrum supplied with the EGS distribution.[19] The ^{60}Co unit phase space data were generated at 100 cm for a 10×10 cm^2 field. In modeling the radiation sources, values of ECUT and PCUT were 0.7 and 0.01 MeV, respectively.[11] Although the HT energy spectrum has a higher contribution of low energy photons, the increase in the very low part of the spectrum (i.e., below 100 keV) is insignificant from that of a conventional 6 MeV linear accelerator and thus the EGSNRC codes are expected to provide accurate results.

2. The value of %dd(10)$_x$ and beam profiles

The value of %dd$(10)_x$ and beam profile were modeled using the DOSXYZnrc user code.[20] The %dd$(10)_x$ calculations were performed in a $30\times30\times30$ cm^3 virtual water phantom. For HT, energy deposited was scored in $4\times4\times1$ mm^3 voxels (1 mm along the beam's central axis, 4 mm in the directions orthogonal to the beam). For ^{60}Co and Varian 21EX, where the beam is much flatter, the cross section of the scoring voxels was $20\times20\times1$ mm^2. Range rejection was employed with an ESAVIN value of 0.8 MeV. DOSXYZNRC's nonuniform padding around the scoring voxels was also used. ECUT and PCUT were set to 0.7 and 0.01 MeV, respectively.

All physical measurements were performed at the facilities of the Cross Cancer Institute. The value of %dd$(10)_x$ was measured using the A1SL in a water tank of 30×30 cm^2 cross section and 20 cm depth. A shift of 1.2 mm (0.6 r_{cav}) upstream was applied to the depth-dose curve. The absorbed dose was integrated over a 10 s period at each depth. An in-air measurement was taken simultaneously in order to correct for any minor output variation from the HT unit.

Dose profiles were measured in a solid water phantom at a depth of 1.5 cm and SSD of 85 cm using Kodak EDR2 film. Film densities were converted to dose using a sensitometric curve. Profile measurements were compared with the profiles calculated using the DOSXYZnrc code. In calculating the dose profiles, the energy deposited was scored in an array of $4\times4\times4$ mm^3 voxels centered at 1.5 cm depth and aligned along both the long and short axes of the field. The dose profile along the long axis of a 5×40 cm^2 field was measured and calculated in order to tune the focal spot.

3. Water-to-air spr

The water-to-air spr for all seven photon beams modeled was calculated using the SPRRZnrc user code.[21–23] The spr values were calculated in a virtual cylindrical water phantom of 20 cm radius and 30 cm depth. The simulated beam dimensions were significantly smaller than 20 cm. A cylindrical scoring voxel of 1 cm radius and 0.5 cm thickness was centered at a depth of 10 cm to determine the spr values at that depth. ECUT and PCUT were set to 0.521 and 0.01 MeV, respectively.[21]

4. Air-to-C552 spr

The air-to-C552 spr was determined for the seven different photon beams using the SPRRZnrc user code. A virtual cylindrical phantom of 20 cm radius was used. Cylindrical slabs of C552 3 cm thick (^{60}Co beam) and 5 cm thick (HT

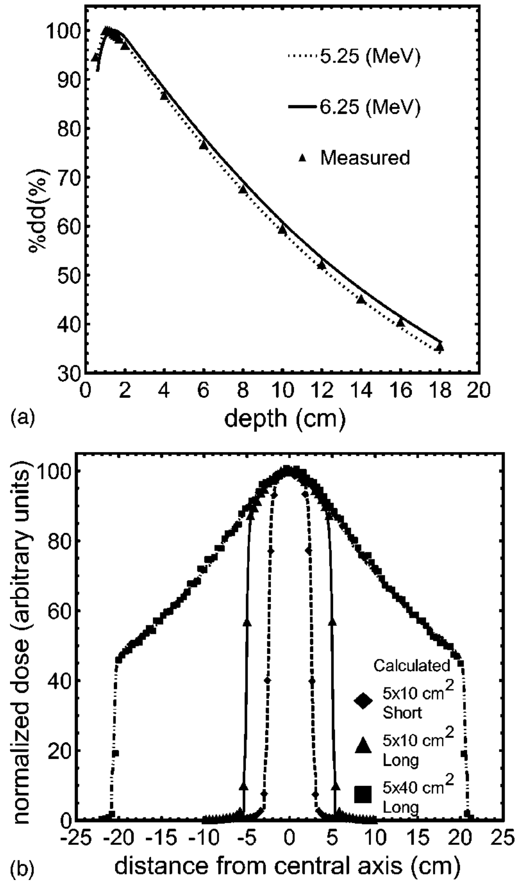

FIG. 3. (a) The calculated percent depth dose curve of the 5.25 and 6.25 MeV HT mean incident electron energy as compared to the measured percent depth dose. (b) The calculated absorbed dose profiles of the HT unit (5.5 MV) compared to the measured profiles of the HT unit. Measurements were made with Kodak EDR2 film. Lines are the measured data of their corresponding calculated values.

and Varian 21EX beams) were placed between 10- and 20-cm-thick cylindrical slabs of water. The photon beams were incident on the surface of the first, i.e., 10-cm-thick water slab. The cylindrical scoring voxel of 1 cm radius and 0.5 cm thickness was placed in C552 at a depth of 11.25 cm for the ^{60}Co beam and 12.25 cm for the HT unit and the Varian 21EX linear accelerator. This thickness of C552 was sufficient to ensure that the electrons for which the spr was determined were those originating in the C552. The 20 cm thickness of the second water slab following the C552 was used to allow for sufficient backscattered photons. The α term in P_{wall} refers to the fraction of ionization arising from electrons originating in the ion chamber wall.[4] Since the ion-chamber wall is made of C552, we are required to use the C552 water phantom for these calculations.

5. C552-to-water ratio of mean mass energy absorption coefficients

In order to determine the ratio of mean mass energy absorption coefficients, the FLURZnrc user code[21] was used to determine photon fluence spectra in a cylindrical virtual water phantom of radius 20 cm and of thickness 22.5 cm. The

TABLE I. A comparison of values required for the %dd conversion. For the statistical error calculations of k_Q any error less than 0.0001 was rounded up to 0.0001. Error in the α value of $P_{\rm wall}$ or the TG-51 value of k_Q for the Varian 6 MV was not considered. The error in $\%{\rm dd}(10)_{x[\rm HT\ TG\text{-}51]}$ corresponds to the error in k_Q.

Mean incident electron energy (MeV)	$[(\overline{L}/\rho)^{\rm water}_{\rm air} P_{\rm wall}]^{\rm HT\ Calc}_{\rm Varian6\ MV\ Calc}$	$k_{Q[\rm HT\ TG\text{-}51]}$	$\%dd(10)_{x[\rm HT\ Ref]}$	$\%dd(10)_{x[\rm HT\ TG\text{-}51]}$
5.25	1.0030(2)	0.9981(2)	58.8%(3)	59.8%(+16/−6)
5.50	1.0025(2)	0.9976(2)	59.2%(3)	62.2%(+7/−4)
5.75	1.0021(2)	0.9972(2)	59.8%(3)	63.0%(+4/−5)
6.00	1.0017(2)	0.9967(2)	60.4%(3)	63.9%(+4/−4)
6.25	1.0012(2)	0.9963(2)	60.8%(3)	64.6%(+3/−3)

fluence was calculated in a cylinder of radius 2.4 cm and thickness 5 cm centered at a depth of 10 cm along the beam central axis. This large scoring voxel was chosen to minimize the statistical uncertainty of the energy fluence. The difference in the photon spectrum of this larger sampling volume to the sampling volume used in the spr calculations was found to affect the mean mass energy absorption coefficient by less than 0.003%. The photon fluence was binned into 0.1 MeV intervals for the linear accelerator and HT unit and 0.01 MeV intervals for the ^{60}Co unit. The photon fluence was then used to weight the individual values of mass energy absorption coefficients $\mu_{\rm en}/\rho$ of the medium:[24]

$$(\mu_{\rm en}/\rho)_{\rm medium} = \frac{\int_0^{E_{\max}} E\bullet\varphi(E)(\mu_{\rm en}/\rho(E))_{\rm medium} dE}{\int_0^{E_{\max}} E\bullet\varphi(E) dE}, \tag{5}$$

where $\varphi(E)$ is the photon fluence spectrum. In the case where National Institute of Standards and Technology (NIST) gave no direct mean mass energy absorption coefficient value for a corresponding energy bin, the mass energy absorption coefficient was interpolated on a log-log scale.[24] The water and C552 mean mass energy absorption coefficient values calculated from Eq. (5) were then used to calculate the ratio of mean mass energy absorption coefficients.

6. Determination of α

Values of α for the Varian 21EX and the ^{60}Co unit were obtained from Lempert *et al.*[8] using the value of $\%{\rm dd}(10)_x$ as the beam quality specifier.[4] The results of the Lempert *et al.* experiment are widely used in various dosimetry protocols.[2,7,9,25] In the case of the HT calculations, the value of $\%{\rm dd}(10)_x$ would not be an appropriate beam quality specifier for α due to both the difference in the measurement geometry and the beam quality. For the HT beams, the calculated value for the water-to-air spr was associated with what would be the TG-51 equivalent value for $\%{\rm dd}(10)_x$.[5] This equivalent $\%{\rm dd}(10)_x$ value was then used to determine α from the data of Lempert *et al.* as is done in TG-51.[4,8] The water-to-air spr was chosen as the beam quality transfer quantity since it represents the most rapidly changing parameter as a function of beam quality and it is relatively insensitive to geometric factors.[22]

III. RESULTS AND DISCUSSION

A. Monte Carlo calculations

1. The value of $\%{\rm dd}(10)_x$ and the beam profile

Calculated values of $\%{\rm dd}(10)_x$ for the ^{60}Co and the Varian 21EX nominal 6 MV beam were 58.4(2)% and 66.6(2)%, respectively, whereas our measured values are 58.6% and 66.7%, respectively. The calculated values of $\%{\rm dd}(10)_{x[\rm HT\ Ref]}$ were found to range between 58.8(3)% and 60.8(3)% for the range of energies simulated [see Fig. 3(a) and Table I]. The statistical uncertainties in the last decimal place are given in brackets and represent 1 s.d. The measured value of $\%{\rm dd}(10)_x$ for the HT unit at our center was 59.5% indicating a mean incident electron energy of 5.63 MeV [Fig. 3(a)]. The value of $\%{\rm dd}(10)_x$ for the Varian 21EX under the same reference conditions as our HT unit was calculated to be 62.7(2)% and measured to be 63.0%. Thus the change in reference conditions leads to a change of 3.9% in the value of $\%{\rm dd}(10)_x$ for the Varian 21EX calculation. The calculated $\%{\rm dd}(10)_x$ value of our HT unit (6 MeV) mean incident electron energy was 60.4(3)%, and thus lower than what we calculated for Varian 21EX under the HT reference conditions.

TABLE II. A comparison of our Monte Carlo calculated quantities and the corresponding TG-51 equivalents (Refs. 5,9) to demonstrate the accuracy of our calculations. The values in parentheses are the statistical uncertainties of the last decimal place for the number that they append and represent 1 s.d., i.e., 1.1337(1) is equivalent to 1.1337±0.0001.

Quantity	^{60}Co unit			6 MV Varian 21 EX $\%{\rm dd}(10)_x$=66.6%		
	Present	TG-51	%Diff	Present	TG-51	%Diff
$(\overline{L}/\rho)^{\rm water}_{\rm air}$	1.1337(<1)	1.1335	0.02%	1.1205(<1)	1.1212	0.06%
$(\overline{L}/\rho)^{\rm air}_{\rm C552}$	1.0040(<1)	1.0048	0.08%	1.0174(1)	1.0168	0.06%
$(\overline{\mu_{\rm en}/\rho})^{\rm C552}_{\rm water}$	0.9003(<1)	0.9009	0.07%	0.9018(<1)	0.9016	0.02%

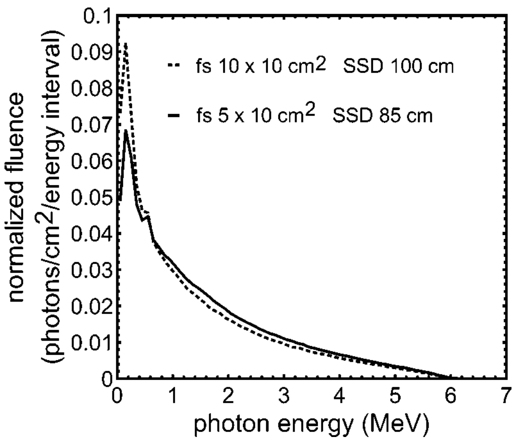

FIG. 4. The photon spectra of the Varian 21EX 6 MV accelerator for two sets of reference conditions. These photon spectra are the same as are used for the mean mass energy absorption coefficient calculation described in sec II. The TG-51 reference conditions result in a higher contribution of low energy photons scattered in from the larger initial primary beam. Here the photon fluence from the FLURZnrc has been normalized such that the sum of the total fluence equals 1.

The difference in $\%dd(10)_{x[\mathrm{HT\ Ref}]}$ obtained with a mean incident electron energy of 6 MeV to the $\%dd(10)_x$ obtained with the Varian 21EX under the HT reference conditions of 85 cm SSD and 5×10 cm^2 field is 2.3%. In comparing the measured and calculated beam profiles of the 5×10 cm^2 field, the calculated FWHM agrees with the measured FWHM to within 1.5 mm along the long axis and 0.05 mm along the short axis [Fig. 3(b)]. The calculated full width 80% maximum agrees with the measured to within 2 mm of the long axis and 2.3 mm of the short axis [Fig. 3(b)]. Also shown is the long axis dose profile comparison for a 5×40 cm^2 field [Fig. 3(b)].

2. Calculation accuracy

The water-to-air spr's for the ^{60}Co unit and the Varian 21EX conventional medical linear accelerator were found to be 1.1337 (<1) and 1.1205 (<1), respectively; these are within 0.02% and 0.06% of the values used by TG-51 in determination of k_Q—Ref. 5 (Table II). The air-to-C552 spr's for the ^{60}Co and 6 MV Varian 21EX linear accelerator were found to be 1.0040(1) and 1.0174(1), respectively. These values are within 0.08% and 0.06% respectively, of the values used by TG-51 in determination of k_Q—Refs. 6, 9 (Table II). The C552-to-water ratio of mean mass energy absorption coefficients for the ^{60}Co and 6 MV linear accelerator were found to be 0.9003 (<1) and 0.9018 (<1), respectively. The calculated numbers agree to within 0.07% for ^{60}Co and 0.02% for the Varian 21EX with the values used in calculating k_Q for TG-51.[9] Our calculated values used in the definition of the wall correction factor given in Eq. (3) yield a value of P_{wall} for the A1SL of 0.9796 in a ^{60}Co beam and of 0.9829 for the Varian 21EX. Our P_{wall} values agree to within 0.12% for the ^{60}Co unit and 0.01% for the Varian 21EX to P_{wall} generated using the TG-51 data[5,9] (Table II). It should be noted that the air-to-C552 spr and the C552-to-water ratio of mean mass energy absorption coefficients for ^{60}Co agree to within 0.01% of more recent calculations[26,27] although our discrepancies with the corresponding TG-51 values are slightly larger.

3. Effect of change in reference conditions

In this section, we determine the effect of changing the reference conditions on the dosimetric quantities for the Varian 21EX. This was done to determine what portion of the change in k_Q is due to the difference in measurement setup. To accomplish this, we compare the values of the water-to-air spr, air-to-C552 spr, as well as the C552-to-water ratio of mean mass energy absorption coefficients calculated for both the HT reference conditions and the TG-51 reference conditions. The water-to-air spr calculation using the Varian 21EX phase space data generated under HT reference conditions (5×10 cm^2 field at an 85 cm SSD) yielded a value of 1.1197(1). This value was 0.07% lower than our calculation for the same linear accelerator under TG-51 reference conditions. The decrease in spr indicates a slightly higher mean energy beam under the the HT reference conditions. This is primarily because of the smaller FS with the HT reference conditions. The air-to-C552 spr which was calculated for the Varian 21EX under the HT reference conditions yielded a value of 1.0182(1), which is 0.08% greater than our calculated value for the TG-51 reference conditions. This increase further indicates a slightly greater mean energy of the beam in the Varian 21EX with HT reference conditions. The calculated C552-to-water ratio of mean mass energy absorption coefficients was identical under the two reference conditions. This is because this ratio is very insensitive to the difference in beam quality over the region of interest as compared to the both the water-to-air spr and

TABLE III. The Monte Carlo calculated quantities required for the determination of P_{wall} and k_Q for different mean incident electron energies of the HT unit. The calculations are carried out under the reference conditions of 85 cm SSD and a 5×10 cm^2 field.

Mean incident electron energy (MeV)	$(\overline{L}/\rho)^{\mathrm{water}}_{\mathrm{air}}$	$(\overline{L}/\rho)^{\mathrm{air}}_{\mathrm{C552}}$	$(\overline{\mu_{\mathrm{en}}}/\rho)^{\mathrm{C552}}_{\mathrm{water}}$	α	P_{wall}
5.25	1.1250(1)	1.0132(1)	0.9011(<1)	0.68	0.9819(1)
5.50	1.1240(1)	1.0141(1)	0.9012(<1)	0.66	0.9823(1)
5.75	1.1233(1)	1.0148(1)	0.9013(<1)	0.65	0.9825(1)
6.00	1.1225(1)	1.0155(1)	0.9014(<1)	0.64	0.9827(1)
6.25	1.1216(1)	1.0164(1)	0.9015(<1)	0.62	0.9831(1)

air-to-C552 spr.[9] When the same value of α (0.62) as used in the TG-51 was used to calculate P_{wall} for the HT reference conditions, the value did not change. Finally the $(\overline{L}/\rho)_{\mathrm{air}}^{\mathrm{water}} P_{\mathrm{wall}}$ value for the Varian 21EX calculated under the HT reference conditions differed from the value calculated under the TG-51 reference conditions by 0.07%, again indicating a higher energy beam. The major factor in the difference of the spr's values is the difference of the number of lower energy scattered photons when calculated using the different FS of the two reference conditions. The smaller FS has lower number of lower energy scattered photons (Fig. 4).

4. Tomotherapy results

The water-to-air spr values for the HT beam decreased by 0.3% as the mean incident electron energy varied from 5.25 to 6.25 MeV (see Table III). The water-to-air spr for the 6.0 MeV mean incident electron energy is 0.25% greater than for the Varian 21EX under the same reference conditions. Over the same 5.25–6.25 MeV range, the air-to-C552 spr values for the HT calculations increased by 0.32% (see Table III). The air-to-C552 spr value for the 6.0 MeV mean incident electron energy is 0.26% less than for the Varian 21EX under the same reference conditions. The HT calculations for the C552-to-water ratio of mean mass energy absorption coefficients increased by 0.04% as the mean incident electron energy varied from 5.25 to 6.25 MeV (Table III). The calculated value for the HT beam for the 6 MeV mean incident electron energy was 0.04% less than that of the Varian 21EX under the same reference conditions. The value of α determined for the HT unit decreased by 9.7% as the mean incident electron energy increased from 5.25 to 6.25 MeV (Table III). The calculated value of α for HT unit's 6.0 MeV mean incident electron energy beam was 3.2% greater than the calculated value for the Varian 21EX. This difference affects the value of P_{wall} by 0.1%. Using the values in Eq. (3), P_{wall} was found to increase from 0.9819 to 0.9831 with an increase of mean incident electron energy from 5.25 to 6.25 MeV (Table III). The HT-to-Varian 21EX ratio of the $(\overline{L}/\rho)_{\mathrm{air}}^{\mathrm{water}} \mathrm{P}_{\mathrm{wall}}$ product was found to decrease by 0.18% as the mean incident electron energy increased from 5.25 to 6.25 MeV (Table I). When multiplied by the Varian 21EX TG-51 value for k_Q, the HT calibration value of k_Q decreased from 0.9981 to 0.9963 as the mean incident electron energy increased from 5.25 to 6.25 MeV (Table I). These values of k_Q for the HT unit correspond to values of $\%\mathrm{dd}(10)_{x[\mathrm{HT\ TG\text{-}51}]}$ that range from 59.8% to 64.6% (Table I). These values of $\%\mathrm{dd}(10)_{x[\mathrm{HT\ TG\text{-}51}]}$ were plotted (Fig. 5) versus the original DOSXYZnrc determined $\%\mathrm{dd}(10)_{x[\mathrm{HT\ Ref}]}$ and fit to a third-order polynomial expressed by Eq. (6),

$$\begin{aligned}\%\mathrm{dd}(10)_{x[\mathrm{HT\ TG\text{-}51}]} = {} & 1.35805 \times \%\,\mathrm{dd}(10)_{x[\mathrm{HT\ Ref}]}{}^3 \\ & - 244.493 \times \%\,\mathrm{dd}(10)_{x[\mathrm{HT\ Ref}]}{}^2 \\ & + 14672.98 \times \%\,\mathrm{dd}(10)_{x[\mathrm{HT\ Ref}]} \\ & - 293\,479.4. \qquad (6)\end{aligned}$$

The maximum error in the fit of Eq. (6) is 0.3%, which results in an error of 0.02% in k_Q. This is obtained by inspecting the maximum slope in the region of interest of the graph of Fig. 2 with $\%\mathrm{dd}(10)_{x[\mathrm{HT\ TG\text{-}51}]}$ on the "x axis." It should be noted that this conversion equation is only valid for $\%\mathrm{dd}(10)_{x[\mathrm{HT\ Ref}]}$ between 58.8% and 60.8% as outside this range the polynomial changes drastically.

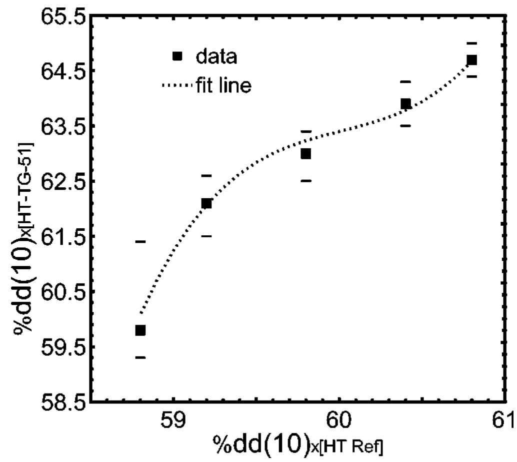

FIG. 5. $\%dd(10)_{x[\mathrm{HT\ TG\text{-}51}]}$ vs $\%dd(10)_{x[\mathrm{HT\ Ref}]}$ for the Exradin A1SL ion chamber. The error bars for the $\%\mathrm{dd}(10)_{x[\mathrm{HT\ TG\text{-}51}]}$ correspond to the error in k_Q that was used to determine $\%dd(10)_{x[\mathrm{HT\ TG\text{-}51}]}$.

B. Summary

This section gives a simple step-by-step protocol for incorporating this work into the TG-51 protocol.

(1) Using the A1SL, measure $\%\mathrm{dd}(10)_{x[\mathrm{HT\ Ref}]}$ in water under the reference conditions of SSD=85 cm and FS=5 $\times$10 cm^2 defined at the phantoms surface. This measurement should incorporate the appropriate chamber shift as described in the TG-51 protocol
(2) Determine $\%\mathrm{dd}(10)_{x[\mathrm{HT\ TG\text{-}51}]}$ from $\%\mathrm{dd}(10)_{x[\mathrm{HT\ Ref}]}$ using either Eq. (6) or Fig. 5. The result should be an increase in $\%\mathrm{dd}(10)_x$ of between 0.6% and 3.8%.
(3) Apply TG-51 as written, using $\%\mathrm{dd}(10)_{x[\mathrm{HT\ TG\text{-}51}]}$ determined in step 2.

Note: as the standard k_Q for the A1SL ion chamber is not included in the TG-51 document, the k_Q listed in Fig. 2 may be used.

IV. CONCLUSION

Due to the design of the HT unit, setting the TG-51 reference SSD of 100 cm is impractical and the reference field of 10$\times$10 cm^2 is impossible. This reference setup is required for the measurement of $\%\mathrm{dd}(10)_x$ used for the k_Q look up table. In addition, the absence of a flattening filter within the HT unit also makes the beam different in terms of both beam flatness and energy spectrum from that of conventional medical linear accelerators. For these reasons, a $\%\mathrm{dd}(10)_x$ conversion for the Exradin A1SL has been created to allow for an HT unit $\%\mathrm{dd}(10)_x$ measured under the reference conditions of 85 cm SSD and 5$\times$10 cm^2 field to be converted to an equivalent $\%dd(10)_x$ to determine k_Q within the TG-51 protocol. The value of $\%dd(10)_{x[\mathrm{HT\ Ref}]}$ was measured to be 59.5%, which indicated that the mean incident electron energy of our HT is 5.63 MeV. From Eq. (6) and our measured value for $\%dd(10)_{x[\mathrm{HT\ Ref}]}$, $\%dd(10)_{x[\mathrm{HT\ TG\text{-}51}]}$ becomes 62.8%, which yields a value for k_Q of 0.9973 (Fig. 2). This value of k_Q is 0.1% lower than that calculated if the measured $\%dd(10)_{x[\mathrm{HT\ Ref}]}$ was used instead of $\%dd(10)_{x[\mathrm{HT\ TG\text{-}51}]}$. Throughout the range of mean incident electron energies for which calculations were done, the corrections increase from only 0.06% to 0.16%. This is because k_Q vs $\%dd(10)_x$ varies slowly in this energy region.

This conversion of the $\%dd(10)_{x[\mathrm{HT\ Ref}]}$ values is expected to hold roughly for other chambers as the water-to-air spr is a good indicator of the air-to-C552 spr,[6,9,27] the ratio of mean mass energy absorption coefficients varies only slightly through the energy range studied and α is material insensitive. It should be noted that the statement $P_{\mathrm{repl[HT]}} = P_{\mathrm{repl[Varian\ 6\ MV]}}$ becomes less true for larger diameter chambers with the maximum error being approximately 0.05%. In addition, our values for the C552-to-air spr can differ from those used in TG-51 up to 0.1% as the value of $\%dd(10)_x$ decreases from 66.6%. Our values, however, agree with more recent calculations.[26,27] Furthermore, throughout the energy range studied, the central electrode correction factor for a 1 mm aluminum electrode would vary by 0.03%.[4] Thus, errors on the order of 0.1% would be expected as the value of $\%dd(10)_x$ decreases from 66.6%. The larger chamber may also result in increased error due to volume averaging in measuring $\%dd(10)_x$ because of the nonuniform field of the HT unit.

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