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Prediction of Stopping-Power Ratios in Flattening-Filter Free Beams

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Abstract

Purpose: In recent years, there has been an increasing interest in flattening-filter free (FFF) beams. However, since the removal of the flattening filter will affect both the mean and the variance of the energy spectrum, current beam-quality specifiers may not be adequate for reference dosimetry in such beams. The purpose of this work was to investigate an alternative, more general beam-quality specifier.

Methods: The beam-quality specifier used in this work was a combination of the kerma-weighted mean and the coefficient-of-variation of the linear attenuation coefficient in water. These parameters can in theory be determined from narrow-beam transmission measurements using a mini-phantom "in-air", which is a measurement condition well suited also to small and non-standard fields. The relation between the Spencer-Attix stopping power ratios and this novel beam-quality specifier was described by a simple polynomial. For reference, we used Monte Carlo calculated spectra and stopping-power data for nine different beams, with and without flattening filter.

Results: The polynomial coefficients were obtained by least square optimization. For all beams included in this investigation, the average of the differences between predicted and Monte Carlo calculated stopping-power ratios was 0.02±0.17% (1SD) (including TomoTherapy and CyberKnife example beams).

Conclusion: An alternative dual-parameter beam-quality specifier was investigated. Our evaluation suggests that it can be used successfully to predict stopping-power ratios in FFF as well as conventional beams, regardless of filtration.

Introduction

In recent years, there has been an increasing interest in flattening-filter free (FFF) beams. With the introduction of intensity-modulated radiotherapy, there is no longer a need for using flattening filters to adjust the beam profile. Instead, the desired fluence profile can be modulated by moving collimators. Flattening-filter free beams have several potential advantages such as increased beam output, less head-scattered dose to the patient, and less beam-quality variations within the beam.[1-8]

However, the altered beam-quality may also have implications for the reference dosimetry of flattening-filter free beams, most notably the Spencer-Attix restricted water-to-air mass collision stopping-power ratio, $\left(\bar{L}/\rho\right)_{air}^{water}$. The removal of the flattening filter results in a softer beam (*i.e.* a lower mean energy), but it also affects the variance of the energy spectrum. Given a certain mean value, less filtration generally corresponds to larger variance, which in turn will result in a lower stopping-power ratio.[9,10] Current beam-quality specifiers, such as $\%dd10_x$ in AAPM's TG-51[11] and TPR_{10}^{20} in IAEA's TRS 398 Code of Practice,[12] do not include any measure of the variance of the energy spectrum, and, therefore, may not be able to predict $\left(\bar{L}/\rho\right)_{air}^{water}$-values in FFF-beams properly.

This question was recently investigated by Xiong and Rogers.[13] They concluded that the standard relationship in the TG-51 protocol between $\%dd10_x$ and $\left(\bar{L}/\rho\right)_{air}^{water}$ can be used with acceptable deviations also for FFF-beams, although they suggested a new relationship, which could be used to further reduce the errors. For the relation between TPR_{10}^{20} and $\left(\bar{L}/\rho\right)_{air}^{water}$, however, they found larger deviations between beams with and without flattening-filter, and it was concluded that k_Q-values determined according to the TRS 398 Code of Practice should not be used in FFF-beams without corrections.[13]

An IAEA working group is currently in the process of developing a new Code of Practice for small and non-standard fields. In their recent progress report,[14] they also raise the issue that FFF-beams have softer energy spectrum than the conventional beams for which current high-energy x-ray dosimetry protocols are developed. TomoTherapy and CyberKnife beams were mentioned as particular examples. In these beams, the reference conditions for which $\%dd10_x$ and TPR_{10}^{20} are defined cannot be established.

We have previously reported on a more general beam-quality measure consisting of two parts, which describes not only the mean but also the variance of the spectrum.[10] These data can in theory be determined by simple measurements using a mini-phantom. In this work, we hypothesise that this dual measure could be useful as a novel beam-quality specifier to predict $\left(\bar{L}/\rho\right)_{air}^{water}$ in FFF as well as conventional beams, regardless of filtration. As a test, the method was also applied to published data for one TomoTherapy machine and one CyberKnife unit.

Materials and Methods

In this work, it is assumed that the relative primary kerma, $K_P(z)/K_P(0)$, where z is the depth in the phantom, can be obtained from measurements. Such measurements can be said to be "in-air equivalent".[15] In this theoretical evaluation, we are not primarily concerned with practical issues related to the measurements, but it is of interest to note, that relative narrow-beam transmission measurements using a mini-phantom, under certain conditions can be "in-air equivalent".[15] In this case, transmission measurements at two different depths (*e.g.* z=20 cm and z=40 cm) will be enough to determine the two polynomial coefficients of the following exponential[10] (see also Refs. 9,16,17):

$$\frac{K_P(z)}{K_P(0)} = e^{a_1 z + a_2 z^2}. \qquad \text{Eq. (1)}$$

In the following, the beam-quality of an incident beam (*i.e.* depth z=0) is assumed to be completely described by the relative primary kerma differentiated with respect to the linear attenuation coefficient in water, $\frac{1}{K_P(0)}\frac{dK_P(0)}{d\mu}$.[10] This distribution can be quantitatively described in terms of its mean ($\bar{\mu}$) and coefficient-of-variation (c_v):

$$\begin{aligned} \bar{\mu} &= \int_\mu \frac{1}{K_P(0)}\frac{dK_P(0)}{d\mu}\mu d\mu \\ c_v &= \frac{1}{\bar{\mu}}\sqrt{\int_\mu \frac{1}{K_P(0)}\frac{dK_P(0)}{d\mu}(\mu-\bar{\mu})^2 d\mu} \end{aligned}. \qquad \text{Eq. (2)}$$

We have previously shown that these two parameters can be derived from the measureable coefficients in Eq. (1) according to[10] (see also Ref. 9):

$$\bar{\mu} = -a_1$$
$$c_v = -\frac{\sqrt{2a_2}}{a_1} \; . \qquad \text{Eq. (3)}$$

In our earlier work, we have investigated the relation between $\bar{\mu}$ and c_v and the Spencer-Attix restricted water-to-air mass collision stopping-power ratio, $\left(\bar{L}/\rho\right)_{air}^{water}$. These data were determined for a large number of known spectra, and a simple polynomial was fit to the data points according to:[10]

$$\left(\bar{L}/\rho\right)_{air}^{water} = b_1 + b_2\bar{\mu} - b_3\bar{\mu}^2 + b_4\bar{\mu}^3 - b_5 c_v \; . \qquad \text{Eq. (4)}$$

For the purpose of this work, the coefficients of Eq. (4) were re-evaluated for flattening-filter free beams. The data for this analysis was based on Monte Carlo calculations performed by Xiong and Rogers,[13] and kindly provided to us by Rogers and his colleagues. These data included spectra and $\left(\bar{L}/\rho\right)_{air}^{water}$ –values for nine different beams from 4 MV to 25 MV, with and without flattening filter, see Table 1. For full details on these calculations, please refer to Ref. 13. Briefly, BEAMnrc/EGSnrc was used to calculate a phase-space file for the photons incident on a water phantom with SSD=100 cm. This phase-space file was then used in a second calculation with the user code SSPRRZnrc in order to determine the value of $\left(\bar{L}/\rho\right)_{air}^{water}$. In this calculation, the full three-dimensional geometry was used, including the variation of the beam profile and the energy spectrum across the field. The statistical uncertainties in the calculated stopping-power ratios are less than 0.01%.[13] Secondly, the phase-space file was used to obtain the energy spectrum averaged over the entire 10x10 cm^2 field. This spectrum was then used in this work to determine the mean ($\bar{\mu}$) and the coefficient of variation (c_v) according to Eq. (2) for all the nine different beams, and new coefficients of Eq. (4) were refitted by using least-square optimization in Matlab.

In order to test the applicability of Eq. (4), it was also applied to published Monte Carlo calculated spectra for a TomoTherapy machine[18] and a CyberKnife unit.[19] For the TomoTherapy machine a stopping-power ratio of $(\bar{L}/\rho)_{air}^{water}$ =1.1225 was calculated by Thomas *et al*,[18] and for the CyberKnife unit a value of $(\bar{L}/\rho)_{air}^{water}$ =1.1194 was calculated by Araki.[19]

Results

For each of the nine beams (with and without flattening filter), the mean ($\bar{\mu}$) and the coefficient of variation (c_v), as calculated from the Monte Carlo simulated spectral distributions according to Eq. (2), are given in Table 2. The coefficients of Eq. (4) were determined as: b_1=0.9441, b_2=8.655, b_3=128.8, b_4=671.4, and b_5=0.05140. The stopping-power ratios predicted by this fit are given in Table 2 together with the deviations from the Monte Carlo calculated values (shown within parentheses).

The predicted stopping-power ratios are also plotted together with the Monte Carlo calculated data in Figure 1. In Figure 2, the same data are shown in a 3D plot in order to illustrate how the $\left(\bar{L}/\rho\right)_{air}^{water}$ -values depend on both the mean ($\bar{\mu}$) and the coefficient of variation (c_v) for the different beams. Please note that this 3D-representation is just for illustration, and that the gridded surface has been extended outside the fitting domain for better visualization. However, the extrapolation of Eq. (4) into these areas is not recommended.

The root mean square deviation between the predicted and Monte Carlo calculated stopping-power ratios was 0.20% and the maximum deviation was 0.37% (Siemens 18 MV) for beams with flattening filter. For the FFF-beams, the root mean square deviation was 0.13% and the maximum deviation was 0.23% (Elekta 25 MV).

The results using of Eq. (4) for a TomoTherapy machine and a CyberKnife unit are also shown in Table 2 and Figure 1. The differences between predicted and MC-calculated $\left(\bar{L}/\rho\right)_{air}^{water}$ -values for these beams were 0.14% and 0.17%, respectively.

Including all the beams in this investigation, the average of the differences between predicted and Monte Carlo calculated stopping-power ratios was 0.02±0.17% (1SD).

Discussion

The linear attenuation coefficient (or the half-value layer, HVL) has been proposed as a beam-quality index several times in the past.[9,20,21] Describing the fundamental properties of the beam, it is an excellent measure of both the primary and scatter dose components, and useful for many purposes. For instance, it has been used with great success as the fundamental parameter of dose calculation engines, in particular for quality control of measured beam data[22] and for independent checking of treatment-planning calculations.[23] For polyenergetic x-ray beams, however, the linear attenuation coefficient will have a distribution, of which also the variance will have an influence on the stopping-power ratio.[9,10] Therefore, in this work we use both its mean ($\bar{\mu}$) and the coefficient-of-variation (c_v). Our results show that such a dual measure has the potential to better predict $\left(\bar{L}/\rho\right)_{air}^{water}$ in FFF-beams as well as in conventional beams, regardless of filtration. In particular, one can note the excellent agreement for the lowest beam energies (4 and 6 MV) and for the TomoTherapy and CyberKnife beams tested with this method.

Thus, the beam-quality specifier investigated in this work seems to be advantageous as compared to the existing measures TPR_{10}^{20} and %dd10$_x$. According to the investigation by Xiong and Rogers,[13] the relationship between $\left(\bar{L}/\rho\right)_{air}^{water}$ and TPR_{10}^{20} for FFF-beams differs with up to 1% as compared to conventional beams. They concluded, therefore, that the TRS 398 Code of Practice should not be used in FFF-beams without corrections. In the same study it was found that, although the $\left(\bar{L}/\rho\right)_{air}^{water}$ increases in FFF-beams, there is a corresponding decrease in $\%dd10_x$ and, therefore, that the relationship is retained. Hence, it was concluded that the TG-51 protocol may still be used with acceptable deviations. Slight deviations, however, were found in the low-energy range (which is probably where most flattening-filter free beams will be found), and a new modified relation was suggested. Also with this new relation, however, linearity does not hold in the low-energy range. Flattening-filter free 6-MV beams are in the very end of the linear interval, and 4-MV beams are well outside.

The spectra and the stopping-power ratios used in this study were taken from previous publications.[13,18,19] In these investigations extensive Monte Carlo simulations, including the relevant treatment head components, were made in order to incorporate the effects of realistic off-axis fluence and energy distributions on the stopping-power ratios. However, as it was not in their interest at the time, these authors did not model the mini-phantom transmission measurement geometry. Therefore, we based our analysis on the available spectra, which in all cases were averaged over a certain field area at the phantom surface (10x10 cm^2 at SSD=100 cm for the linac beams, 5x10 cm^2 at SSD=85 cm for the TomoTherapy machine, and Ø=60 mm at SSD=80 cm for the CyberKnife unit). Although this is surely a limitation of the present investigation, we believe that it may still be representative for "in-air" measurements with a mini-phantom.

We have previously shown that the kerma-weighted mean ($\bar{\mu}$) and coefficient-of-variation (c_v) of the linear attenuation coefficient in water can, in theory, both be obtained from narrow-beam transmission measurements using a mini-phantom "in-air".[10,15] This might be a measurement condition better suited to small and non-standard fields. In fact, the reference conditions for which $\%dd10_x$ and TPR_{10}^{20} are defined cannot be established for TomoTherapy and CyberKnife beams.[14] In contrast, transmission measurements can be performed at short distances using a well collimated beam.[21,24] For HVL-measurements using this geometry, the total measurement uncertainty has recently been estimated to be within 1.5%.[24] This is probably a valid estimate also for measurements of the average of the linear attenuation coefficient. In particular for the coefficient-of-variation, however, the experimental conditions are not yet fully explored, and further investigations will be needed in order to determine an optimal and practical measurement geometry. This will require extensive Monte Carlo calculations (similar to Ref. 15) in order to interpret the measurement results for each beam geometry in an iterative process, efficiently approaching narrow-beam conditions while observing practical constraints.

Conclusions

In this work, we have investigated the primary-kerma weighted distribution of the linear attenuation coefficient in water for flattening-filter free beams. This distribution was quantified in terms of its mean and coefficient-of-variation, ($\bar{\mu}$, c_v). It was shown that these two parameters can be used to predict stopping-power ratios, $\left(\bar{L}/\rho\right)_{air}^{water}$, with high accuracy, regardless of filtration. In particular, an excellent agreement was observed for the lowest beam energies (4 and 6 MV) and for the TomoTherapy and CyberKnife beams included in this work. Taking all the beams studied in this work into account, the agreement between predicted and Monte Carlo calculated stopping-power ratios was on average 0.02±0.17% (1SD). Since the primary-kerma weighted linear attenuation coefficient can theoretically be obtained from simple narrow-beam transmission measurements, we believe that the dual measure investigated here may have a potential as a novel beam-quality specifier well suited for small and non-standard fields. Before practical applications, however, the optimal beam geometry for such measurements needs to be further investigated.

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Table 1. Nine different beams with and without flattening filter were used in this study. Data according to "Method 1" from Xiong and Rogers.[13]

		$\left(\bar{L}/\rho\right)_{air}^{water}$ **-values from Rogers**	
Machine	**Beam quality (MV)**	***With filter***	***Without filter***
Varian	4	1.1293	1.1313
Varian	6	1.1211	1.1240
Varian	10	1.1054	1.1120
Varian	15	1.0998	1.1018
Varian	18	1.0925	1.0959
Siemens KD2	6	1.1201	1.1224
Siemens KD2	18	1.0969	1.1034
Elekta SL25	6	1.1191	1.1219
Elekta SL25	25	1.0830	1.0878

Table 2. The mean ($\bar{\mu}$), coefficient of variation (c_v), and the predicted stopping-power ratios (according to Eq. (4)) for the nine beams used in this study. Percentage deviations from Monte Carlo calculations are given within parentheses.

		With filter			***Without filter***		
Machine	**Beam quality (MV)**	$\bar{\mu}$	c_v	$\left(\bar{L}/\rho\right)_{air}^{water}$ **(% deviation from MC)**	$\bar{\mu}$	c_v	$\left(\bar{L}/\rho\right)_{air}^{water}$ **(% deviation from MC)**
Varian	4	0.0560	0.2287	1.1309 (0.14)	0.0714	0.3436	1.1319 (0.06)
Varian	6	0.0504	0.3198	1.1225 (0.13)	0.0602	0.4319	1.1225 (-0.14)
Varian	10	0.0380	0.4211	1.1021 (-0.30)	0.0502	0.5194	1.1121 (0.01)
Varian	15	0.0350	0.3780	1.0985 (-0.11)	0.0423	0.5343	1.1030 (0.11)
Varian	18	0.0313	0.3504	1.0913 (-0.11)	0.0392	0.5491	1.0976 (0.16)
Siemens KD2	6	0.0483	0.3384	1.1198 (-0.03)	0.0580	0.4348	1.1213 (-0.10)
Siemens KD2	18	0.0333	0.4151	1.0929 (-0.37)	0.0428	0.5055	1.1052 (0.16)
Elekta SL25	6	0.0475	0.3287	1.1196 (0.04)	0.0566	0.4315	1.1208 (-0.10)
Elekta SL25	25	0.0286	0.3167	1.0857 (0.25)	0.0337	0.4824	1.0903 (0.23)
TomoTherapy	6.0*	-	-	-	0.0557	0.3579	1.1241 (0.14)
CyberKnife	6.7*	-	-	-	0.0529	0.3788	1.1213 (0.17)

*Mean incident electron energy.

Figure Captions

Figure 1. Monte Carlo calculated (from Xiong and Rogers,[13] Table 1) and predicted (using Eq. (4)) stopping-power ratios as a function of the spectral mean ($\bar{\mu}$) for the nine different beams, with and without flattening filter, used in this work. One TomoTherapy beam and one CyberKnife beam are also included.

Figure 2. Monte Carlo calculated $\left(\bar{L}/\rho\right)_{air}^{water}$ -values (from Xiong and Rogers,[13] Table 1) as a function of spectral mean ($\bar{\mu}$) and coefficient of variation (c_v) for the nine different beams, with and without flattening filter, used in this work. The gridded surface represents the fitted Eq. (4). Please note that this 3D-representation is for illustration only, and that the gridded surface has been extended outside the fitting domain for better visualization.

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