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Combining tissue-phantom ratios to provide a beam-quality specifier for flattening filter free photon beams

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Short Title: Stopping-power ratios in FFF beams

Keywords: beam-quality specifier, photon beams, stopping-power ratios, flattening filter free

Investigation of TPR ratios as a beam-quality specifier for beams with and without a flattening filter.

Abstract

Purpose: There are currently several commercially available radiotherapy treatment units without a flattening filter in the beam line. Unflattened photon beams have an energy and lateral fluence distribution that is different from conventional beams and thus their attenuation properties differ. As a consequence, for flattening filter free (FFF) beams, the relationship between the beam-quality specifier $TPR_{20,10}$ and the Spencer-Attix restricted water-to-air mass collision stopping-power ratios, $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$, may have to be refined in order to be used with equivalent accuracy as for beams with a flattening filter. The purpose of this work was two-fold. Firstly, to study the relationship between $TPR_{20,10}$ and $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ for FFF beams where the flattening filter has been replaced by a metal plate as in most clinical FFF beams. Secondly, to investigate the potential of increasing the accuracy in determining $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ by adding another beam-quality metric, $TPR_{10,5}$. The relationship between $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ and $\%dd(10)_x$ for beams with and without a flattening filter was also included in this study.

Materials: A total of 24 realistic photon beams (10 with and 14 without a flattening filter) from three different treatment units have been used to calculate $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$, $TPR_{20,10}$ and $TPR_{10,5}$ using the EGSnrc Monte Carlo package. The relationship between $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ and the dual beam-quality specifier $TPR_{20,10}$ and $TPR_{10,5}$, was described by a simple bi-linear equation. The relationship between the photon beam-quality specifier $\%dd(10)_x$ used in the AAPM's TG-51 dosimetry protocol and $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ was also investigated for the beams used in this study, by calculating the photon component of the percentage depth dose at 10 cm depth with SSD 100 cm.

Results: The calculated $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ for beams without a flattening filter was 0.3 % lower, on average, than for beams with a flattening filter and comparable $TPR_{20,10}$. Using the relationship in IAEA TRS-398 resulted in a root mean square deviation (RMSD) of 0.0028

with a maximum deviation of 0.0043 (0.39 %) from Monte Carlo calculated values. For all beams in this study the RMSD between the proposed model and the Monte Carlo calculated values was 0.0006 with a maximum deviation of 0.0013 (0.1 %). Using an earlier proposed relationship (Xiong and Rogers, 2008) between $\%dd(10)_x$ and $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ gave a RMSD of 0.0018 with a maximum deviation of 0.0029 (0.26 %) for all beams in this study (compared to RMSD 0.0015 and a maximum deviation of 0.0048 (0.47 %) for the relationship used in AAPM TG-51).

Conclusions: Using $\text{TPR}_{20,10}$ as a beam quality specifier for the flattening filter free beams used in this study gave a maximum difference of 0.39 % between $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ predicted using IAEA TRS-398 and Monte Carlo calculations. An additional parameter for determining $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ has been presented. This parameter is easy to measure; it requires only an additional dose measurement at 5 cm depth with SSD 95 cm, and provides information for accurate determination of the $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$-ratio for beams both with and without a flattening filter at the investigated energies.

Introduction

Clinical linacs operating in flattening filter free (FFF) mode have been available for some time. More recently, modified conventional linacs, i.e. the TrueBeam beam unit from Varian and the VersaHD from Elekta, have been released with the capability of operating in flattening filter free mode. The main reason for the introduction of these beams is the increased dose rate but there are also other advantages such as reduced lateral beam-quality variation and a reduced head-scatter dose to the patient[1-5].

When the beam hardening flattening filter is removed the lateral fluence fall-off reduces the dose contribution from phantom scattered photons, which affects the attenuation properties of the beam. The spectral composition of the beam is also altered due to the different spectral filtration. The impact of these effects on the ability to predict Spencer-Attix restricted water-to-air mass collision stopping-power ratios $(\bar{L}/\rho)_{\mathrm{air}}^{\mathrm{water}}$ based on $\mathrm{TPR}_{20,10}$ in IAEA's TRS-398 Code of Practice[6] and $\%dd(10)_x$ in AAPM's TG-51[7] have previously been studied[8]. In this study by Xiong and Rogers it was found that the relation between the beam-quality specifier $\%dd(10)_x$ and $(\bar{L}/\rho)_{\mathrm{air}}^{\mathrm{water}}$ still holds for FFF-beams with a worst case error of 0.4 %, even if the relationship could be adjusted to increase the accuracy[8]. However, the authors also reported that when using $\mathrm{TPR}_{20,10}$ to determine $(\bar{L}/\rho)_{\mathrm{air}}^{\mathrm{water}}$, deviations of up to 1 % could be expected, and recommended that it should not be used for FFF beams without corrections.

The beam-quality specifier $\mathrm{TPR}_{20,10}$ is a measure closely related to the mean attenuation coefficient of a photon beam. However, it is not very sensitive to the spectral variance of the incident photon beam[9, 10]. For beams without a flattening filter the photon energy distribution along the central axis will generally be broader[1]. In Fig. 1, tissue-phantom ratio profiles for two beams, both with and without a flattening filter, but with similar $\mathrm{TPR}_{20,10}$, are shown. The different spectral composition and the reduced dose component from laterally scattered photons in FFF beams leads to different attenuation properties.

Our group has previously described and investigated a more general dual–parameter beam-quality specifier[11]. The advantage of this parameter is that not only the mean energy of the spectrum is taken into account, but also the wider energy distribution. It was shown that this novel beam-quality specifier was able to more accurately predict $(\bar{L}/\rho)_{\mathrm{air}}^{\mathrm{water}}$ for FFF beams in narrow beam geometry. In the current study we investigated if a simple extra measured parameter, $\mathrm{TPR}_{10,5}$, can provide this additional information, and together with $\mathrm{TPR}_{20,10}$ be used to increase the accuracy of assigning $(\bar{L}/\rho)_{\mathrm{air}}^{\mathrm{water}}$ to beams without a flattening filter in broad-beam geometry in the energy range of 6 MV to 10 MV.

Material and Methods

Three different models of medical linear accelerators have been used for Monte Carlo simulations using the EGSnrc-package (V4-r2-3-2)[12-14]: Elekta Synergy, Elekta Precise and Varian TrueBeam. The treatment head geometry of the Elekta Synergy, based on specifications provided by the vendor, was modeled in BEAMnrc. For this model, three different beam filters were simulated: the conventional 6 MV flattening filter, a 6 mm thick copper plate and a 2 mm thick stainless steel plate. For each of these configurations six incident electron energies were used (see Table I). The main difference between the Elekta Synergy model and the VersaHD is the collimating system (MLC)[*], which should not influence the calculations. For the Varian TrueBeam and Elekta Precise, IAEA compliant phase spaces were acquired from the vendor[15] and from the public IAEA phase space database[16, 17], respectively. The TrueBeam IAEA phase space files (version 2), scored above

* Personal communication, Magne Johansson, Elekta Oncology Systems, Stockholm, Sweden, 2014

the collimating jaws, were used as inputs to BEAMnrc where the particle transport to a plane below the jaws was simulated. The jaws were modeled according to specifications from the vendor.

Calculations of $TPR_{20,10}$, $TPR_{10,5}$ and $\%dd(10)_x$ were performed in DOSRZnrc. For Elekta Precise and Varian TrueBeam, phase space files scored at SSD 80 cm, 90 cm, 95 cm and 100 cm were used as inputs for the simulations. When calculating $\%dd(10)_x$ only the photon part of the phase space file at SSD 100 cm was used. In the Elekta Synergy simulations the full BEAMnrc simulation was used as a direct input to the dose calculations except for the calculations of $\%dd(10)_x$ where a phase space scored at SSD 100 cm was used. For TPR and $(\bar{L}/\rho)_{\mathrm{air}}^{\mathrm{water}}$ calculations the scoring voxels had a radius of 1 cm and a depth of 0.5 cm. In order to reduce the statistical uncertainty in the TPR simulations, fourth degree polynomials were fitted to the depth dose curves in the range of ±5 cm around the two deepest points of interest (10 cm and 20 cm depth) and from 5 to 10 cm depth for the most shallow dose point at 5 cm depth. These polynomials were then used to calculate the dose in the points of interest. In order to increase the accuracy in the maximum dose when calculating $\%dd(10)_x$, the sampling depth was set to 0.2 cm for depths down to 4 cm and 0.5 cm from 4 cm depth to a depth well beyond 10 cm, while the radius of the voxels was kept at 1 cm. For all $(\bar{L}/\rho)_{\mathrm{air}}^{\mathrm{water}}$simulations a phase space scored at SSD 100 cm was used as the input source.

For the Elekta Synergy model used as input to DOSRZnrc, directional bremsstrahlung splitting was employed with a splitting radius of 12 cm at SSD 100 cm and a splitting number of 1000, with a rejection plane 10 cm above the scoring plane. The phase spaces at SSD 100 cm intended for the SPRRZnrc calculations of $(\bar{L}/\rho)_{\mathrm{air}}^{\mathrm{water}}$ was generated using uniform bremsstrahlung splitting with a splitting number of 20 and without Russian roulette. Pair angular sampling was set to the complete modified Koch-Motz distribution and the XCOM photon cross-sections and NIST bremsstrahlung cross-sections were used in all simulations. The remaining parameters were left at their default values. In simulations using BEAMnrc, the energy cut-off was 10 keV for photons and 711 keV for electrons, including the rest mass. In DOSRZnrc and SPRRnrc simulations the photon cut-off was 10 keV, while the electron energy cut-off was lowered to 521 keV and no range rejection was performed.

The calculated data were fitted to a simple bi-linear equation according to

$$(\bar{L}/\rho)_{\text{air}}^{\text{water}} = a_1 + a_2(\text{TPR}_{20,10}) + a_3(\text{TPR}_{10,5}). \qquad (1).$$

The constants $a_{1\text{-}3}$ were determined by least-square fitting of the data.

Results

Tissue-phantom ratios for two beams, one with and one without a flattening filter, are shown in Fig. 1. For these two beams the calculated $\text{TPR}_{20,10}$ is 0.16 % lower for the FFF beam, which is within the estimated uncertainty, while $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ is 0.2 % lower. As shown in the figure, attenuation properties of the photon beams are different at shallower depths due to the broader energy distribution for the flattening filter free beam, and the difference in lateral scatter. This difference is more easily observed using $\text{TPR}_{10,5}$, which is 1.2 % higher for the conventional beam. The spectral distributions of the two beams are shown in Fig. 2.

For the 24 photon beams (10 with and 14 without a flattening filter) used in this study, $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$, $\text{TPR}_{20,10}$ and $\text{TPR}_{10,5}$ were calculated and the results are presented in Table I. The coefficients of Eq. (1), with 95 % confidence bounds, were determined as a_1= 1.0325±0.0359, a_2= -0.4317±0.0399, a_3= 0.4466±0.0724 which gave a r^2 value of 0.9865. In Fig. 3, Monte

Carlo calculated values for $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ and $TPR_{20,10}$ are shown together with the predicted stopping-power values using Eq (1). The relationship used in TRS-398, Eq. 2 below, is included in the figure for comparison (see figure 23 and ref. 143, 144 in TRS-398[6]).

$$(\bar{L}/\rho)^{\text{water}}_{\text{air}} = 1.36138-1.29629(TPR_{20,10}) +2.53021(TPR_{20,10})^2-1.68964(TPR_{20,10})^3 \qquad (2)$$

Table I. Calculated values of $TPR_{20,10}$, $TPR_{10,5}$, $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ and $\%dd(10)_x$ for all beams in this study. The statistical uncertainties are smaller than 0.15 % in TPR calculations, 0.1 % in $\%dd(10)_x$ and less than 0.01 % for $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$. The assigned letter to each beam is used as reference in Figure 5.

Beam model	Index	Energy	$TPR_{20,10}$	$TPR_{10,5}$	$(\bar{L}/\rho)^{\text{water}}_{\text{air}}$	$\%dd(10)_x$
Elekta Synergy FF	a	5.0	0.6580	0.8398	1.1230	65.85
	b	5.7	0.6731	0.8456	1.1204	67.23
	c	6.3†	0.6840	0.8526	1.1183	68.13
	d	6.6	0.6886	0.8539	1.1172	68.50
	e	7.6	0.7034	0.8608	1.1137	70.26
	f	8.1	0.7090	0.8643	1.1124	71.09
Elekta Precise	g	6	0.6681	0.8452	1.1212	66.67
	h	10	0.7272	0.8747	1.1092	72.51
Varian TrueBeam FF	i	6	0.6664	0.8431	1.1206	66.94
	j	10	0.7353	0.8747	1.1057	74.18
Elekta Synergy 2 mm Fe	k	6.3†	0.6569	0.8300	1.1208	65.84
	l	7.0	0.6678	0.8367	1.1184	67.05
	m	7.9	0.6810	0.8445	1.1154	68.50
	n	8.5	0.6891	0.8475	1.1138	69.22
	o	9.2	0.6970	0.8512	1.1117	70.42
	p	10.0	0.7055	0.8542	1.1093	71.51
Elekta Synergy 6 mm Cu	q	6.3†	0.6633	0.8356	1.1201	66.42
	r	7.0	0.6733	0.8425	1.1178	67.53
	s	7.9	0.6870	0.8479	1.1150	68.71
	t	8.5	0.6937	0.8520	1.1131	69.77
	u	9.2	0.7014	0.8561	1.1109	70.68
	v	10.0	0.7105	0.8583	1.1085	71.82
Varian TrueBeam FFF	w	6	0.6246	0.8118	1.1243	63.13
	x	10	0.6976	0.8487	1.1105	70.88

†Mean incident electron energy that produces photon beams in agreement with measurements at the department of medical physics, Skåne University Hospital, Lund, Sweden.

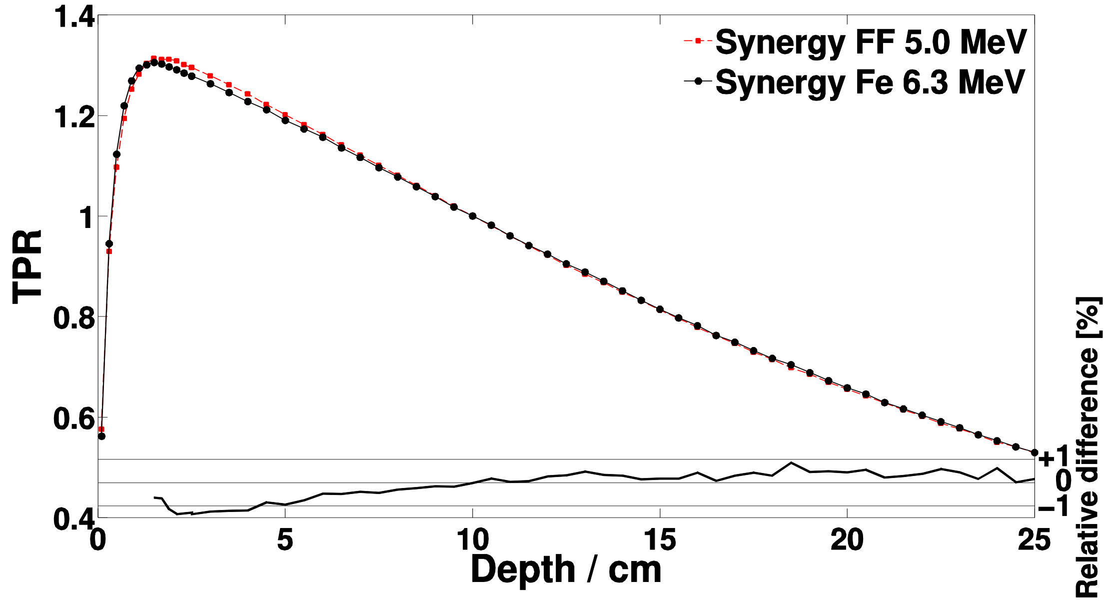

FIG. 1. Tissue-phantom ratios with different depths for a field size of 10x10 cm^2 and a constant SCD of 100 cm, for one flattening filter free beam and one conventional beam with similar $TPR_{20,10}$. The TPR curves are normalised to the dose at 10 cm depth. The statistical uncertainty for each point is within 0.15 %. The spectra for each of these two beams are shown in Fig. 2.

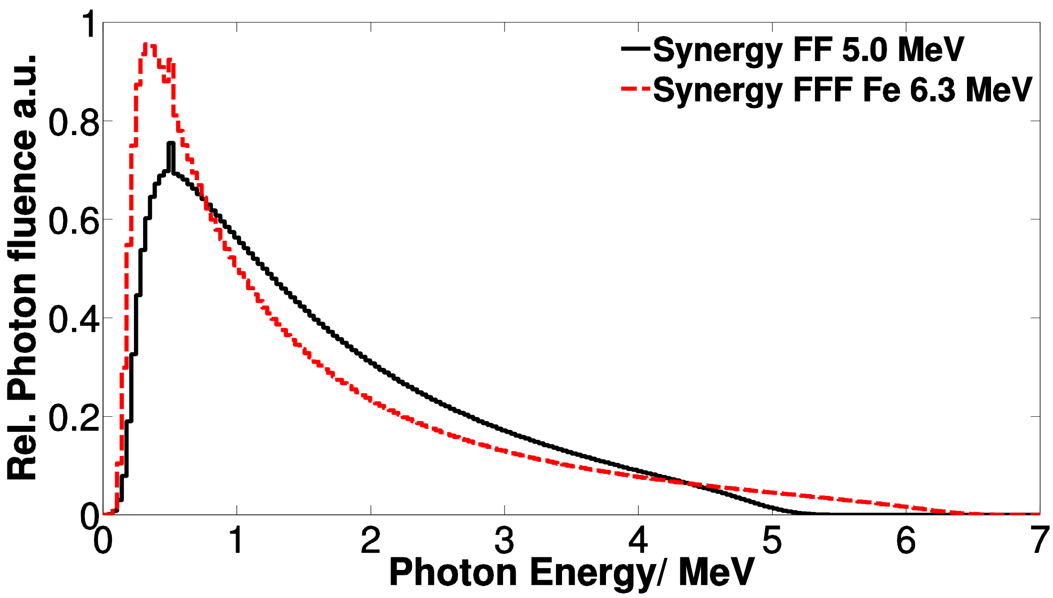

FIG. 2. Spectral distribution of the two beams used to calculate tissue-phantom ratios shown in Fig. 1.

The average relative difference in $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ between beams with and without a flattening filter is of the order 0.3 % at the same value of $TPR_{20,10}$. The root mean square deviation (RMSD) between the calculated $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ of all FFF beams and TRS-398 is 0.0028 with the largest deviation 0.0043 for the TrueBeam 10 MV beam. Comparing calculated stopping-power values to values predicted by Eq. (1), the RMSD is 0.0006 with the largest deviation 0.0013 for the Elekta Synergy beam with 2 mm Fe and incident mean electron energy of 6.3 MeV.

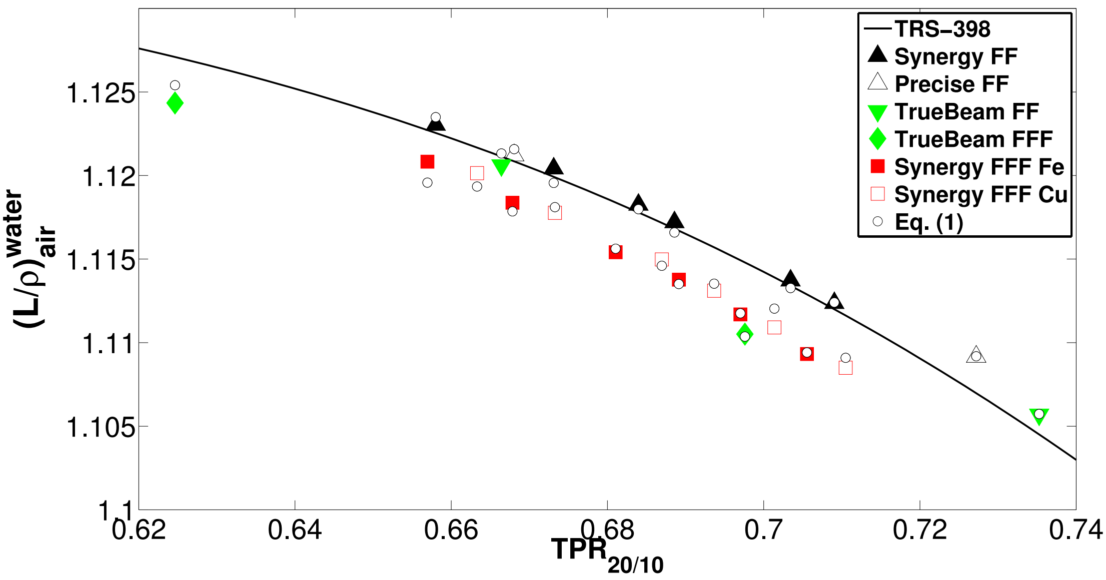

FIG. 3. Monte Carlo calculated stopping-power ratios as a function of $TPR_{20,10}$ for all 24 beams used in this work. Predicted values using both $TPR_{20,10}$ and $TPR_{10,5}$ (Eq. (1)) are shown as circles (in a 3D-representation with an additional axis for $TPR_{10,5}$, these data would appear on a plane surface).

For the conventional beams, the deviation between TRS-398 predicted values and Monte Carlo calculated values is small, with a RMSD of 0.0009 and a largest deviation of 0.0022 for the Elekta Precise 10 MV. For the model used in this work the RMSD is 0.0005 with the largest deviation 0.0009 for the Elekta Synergy with incident beam energy of 5.7 MeV. For all FF and FFF beams the RMSD between Eq. (1) and Monte Carlo calculated $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ is 0.0006.

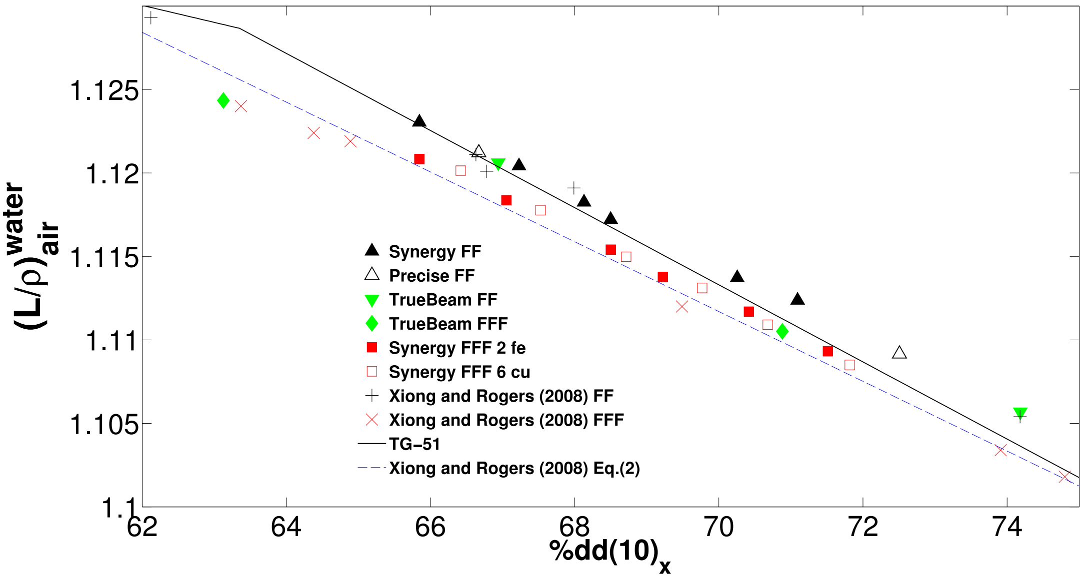

FIG. 4. Calculated $\%dd(10)_x$ and Spencer-Attix mass restricted collision stopping-power ratios, $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ for all beams in this study. Values from Xiong and Rogers (2008) are included as reference (crosses) and the fit from AAPM's TG -51 protocol (solid line). The fit proposed in the paper by Xiong and Rogers is also shown (dashed line).

The calculated values of $(\bar{L}/\rho)^{\text{water}}_{\text{air}}$ and $\%dd(10)_x$ for all beams are presented in Table I and shown in Fig. 4. For comparison, both the relationship used in TG-51[18] (solid line) and the general fit proposed by Xiong and Rogers[8] (dashed line) are included. Data from Table I in the paper by Xiong and Rogers are shown as crosses. For the 10 beams with a flattening filter the RMSD about the TG-51 line is 0.0011 with a largest deviation of 0.0021 for the 10 MV TrueBeam. For the 14 FFF beams in this study the RMSD is 0.0017 with a largest deviation of 0.0048 for the 6 MV TrueBeam. The RMSD for all beams about the TG-51 line is 0.0015.

Comparing the calculated values in this study with the proposed fit in Xiong and Rogers (2008) gives a RMSD of 0.0026 for the FF beams with a largest deviation of 0.0029 (Synergy 8.1 MeV). For the FFF beams the RMSD is 0.0008 with a largest deviation of 0.0017 for the 6 MV TrueBeam. For all beams the RMSD is 0.0018.

In Fig. 5 the relative difference between the Monte Carlo calculated $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$-ratios and predicted ratios using TRS-398 and TG-51 are shown together with the proposal in this study (Eq. 1) and the proposal from Xiong and Rogers (2008) (Eq. 2 in Xiong and Rogers (2008)).

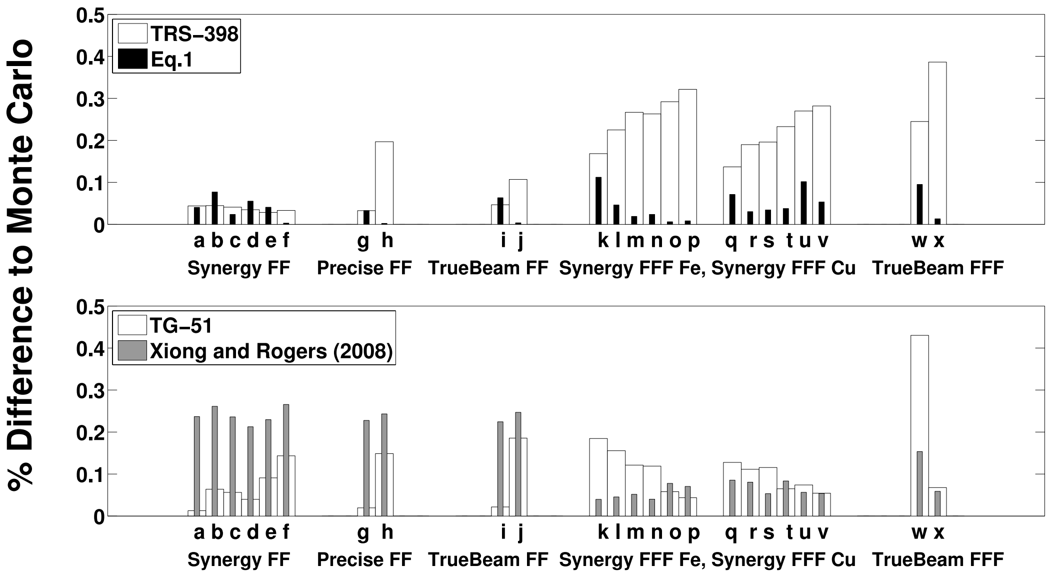

FIG. 5. Difference, in %, between calculated and predicted stopping-power for the beams presented in Table I. The upper plot shows differences using either TRS-398 or Eq. (1) and the lower plot displays differences using the relationships used in TG-51 and the relationship proposed by Xiong and Rogers (2008).

The calculated $TPR_{20,10}$ and $\%dd(10)_x$ were also compared to results from Kalach and Rogers[19] to further investigate the validity of the present simulations. Applying Eq. (3) from that study to our Monte Carlo calculated beam-quality specifiers shows good agreement for the conventional beams with a RMSD of 0.002 and a maximum deviation of 0.004. Kalach and Rogers (2003) had a RMSD of 0.0034 and a maximum deviation of 0.007, although they used beams with different filtration in their fit. For our FFF beams the RMSD was 0.006 with a maximum deviation of 0.01. This would imply that some of the lightly filtered beams used in our study would fall outside of what Kalach and Rogers call "clinic-like" beams.

Discussion

Current dosimetry protocols such as the IAEA TRS-398 Code of Practice and AAPM TG-51 have not primarily been developed for lightly filtered beams such as flattening filter free beams. In this work, we have investigated how the relationship between the beam-quality specifiers $TPR_{20,10}$, $\%dd(10)_x$ and Spencer-Attix mass collision stopping-power ratios is affected by the replacement of the flattening filter with a flat metal plate of different thickness. Monte Carlo simulations performed in the mid-eighties showed that for beams with the same mean attenuation coefficient (a measure closely related to $TPR_{20,10}$) but with different spectral distributions, the stopping-power ratios were affected[9]. This was later studied through graphite calorimetry at NPL[‡] where flat beams with different filtration changed the relationship between $TPR_{20,10}$ and ion-chamber calibration factors[10]. A previous study[8] found that the relationship between $\%dd(10)_x$ and $(\bar{L}/\rho)^{water}_{air}$ used in AAPM TG-51 still holds for flattening filter free beams. The same study also showed that using $TPR_{20,10}$ as a beam-quality specifier for FFF beams the predicted $(\bar{L}/\rho)^{water}_{air}$ differed by up to 1 %. This may have caused an uncertainty about the use of this quality index for the now clinically available FFF-beams.

In this study the largest difference in predicting $(\bar{L}/\rho)^{water}_{air}$ for flattening filter free beams, using the relationship in IAEA TRS-398, was 0.4 %. This is the same difference as Xiong and Rogers (2008) reported as the smallest difference between flattened and unflattened beams at the same $TPR_{20,10}$. One explanation for this is the presence of a metal plate in the FFF beams included in this study, which is more relevant for clinical beams. Clinical FFF beams pass through a metal plate, which acts as a build-up plate for the monitor ion-chamber and also filters out electrons that may have passed through the target[20,21]. It is also important to point

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out that in the study by Xiong and Rogers the energy range of the investigated beams was 4 MV to 25 MV. The difference in $(\bar{L}/\rho)_{\mathrm{air}}^{\mathrm{water}}$ at the same $\mathrm{TPR}_{20,10}$ found in this study is close to the largest chamber specific and field dependent beam-quality correction factor for a lightly filtered beam measured at NPL (0.6 % for a 4 MV lightly filtered beam)[22].

The average difference between Monte Carlo calculated and TRS-398 predicted $(\bar{L}/\rho)_{\mathrm{air}}^{\mathrm{water}}$ was only 0.3 % for flattening filter free beams in our study (RMSD 0.0028). This small deviation can be further improved by using an additional specifier, $\mathrm{TPR}_{10,5}$, based on which a simple bi-linear equation provides a more accurate prediction regardless of beam filtration in the investigated energy range. We have previously demonstrated that a beam-quality specifier that takes into account both the mean energy and the energy distribution of the photon beam spectrum can be used to accurately predict stopping-power ratios for beams with different filtration[11]. In the present study it has been shown that the addition of $\mathrm{TPR}_{10,5}$ accounts for these different attenuation properties for both conventional and flattening filter free beams. If possible, this parameter can be determined at the same time as the other two measures (TPR_{20} and TPR_{10}) for the standard beam quality. It is important to note that in this study photon beams in the energy interval 6 MV to 10 MV have been studied. For beams in a larger interval it is probable that a higher order polynomial will be needed and Eq. 1 may not be valid.

Xiong and Rogers (2008) proposed a new relationship between $(\bar{L}/\rho)_{\mathrm{air}}^{\mathrm{water}}$ and $\%dd(10)_{\mathrm{x}}$ based on beams both with and without flattening filters (Eq. 2 in Xiong and Rogers (2008). For the beams in this study the results using Xiong and Rogers proposed relationship are close to the ones reported in their study. However, Xiong and Rogers studied a much larger energy interval of 4 MV to 25 MV.

We have investigated beams in the low energy range, from 6 MV FFF to 10 MV, where most of the clinical flattening filter beams are tuned. For FFF beams, the TG-51 protocol will give slight deviations that will be reduced using the proposed fit by Xiong and Rogers[8]. For conventional beams the TG-51 relationship gives a better agreement to the Monte Carlo calculated stopping-power values than the proposal made by Xiong and Rogers. The results in this study indicate that using separate relationships between $\%dd(10)_x$ and $(\bar{L}/\rho)_{\mathrm{air}}^{\mathrm{water}}$ for conventional and flattening filter free beams will improve the prediction.

For conventional linacs operating in FFF mode the relationship between $(\bar{L}/\rho)_{\mathrm{air}}^{\mathrm{water}}$ and $\mathrm{TPR}_{20,10}$ is different from regular flattened beams, which has been addressed in this study. For other flattening filter free modalities, such as TomoTherapy and Cyberknife, there is the additional issue that reference conditions stated in, e.g. TRS-398 and TG-51, can not be established. This is a problem that has been previously studied[23,24]. A method for estimating $\mathrm{TPR}_{20,10}$ for a 10x10 cm^2 reference field based on measurements for arbitrary field-sizes has been proposed by Sauer[23]. In this paper it was suggested that the model could be used for flattening filter free beams and data showing this was provided for a TomoTherapy unit, for which a 10x10 cm^2 reference field is not possible to deliver. Sauer found that by correcting the field size for the lack of lateral scatter using scatter-radius data from BJR Suppl. 25[25] good agreement to Monte Carlo calculated $\mathrm{TPR}_{20,10}$ was achieved. This correction was done through estimation from a scatter-ratio figure (Figure A.1 in BJR Suppl. 25). More recently, an addendum to the UK dosimetry code of practice for TomoTherapy reference dosimetry has been published[22]. For the determination of the beam-quality specifier for this unit Palmans'[24] revised version of the method proposed by Sauer[23] is used to correct the $\mathrm{TPR}_{20,10}$ value measured in non-standard conditions. In that protocol, correction is made for the field-size only and not for the beam quality.

Conclusion

In this work we have investigated the relationship between beam-quality specifiers in current Codes of Practices ($TPR_{20,10}$ in IAEA TRS-398 and $\%dd(10)_x$ in AAPM TG-51) and stopping-power ratios for photon beams with and without a filter in the energy range of 6-10 MV. The average difference from the fit of $(\bar{L}/\rho)^{\mathrm{water}}_{\mathrm{air}}$ and $TPR_{20,10}$ used in IAEA TRS-398 was only 0.3% for the flattening filter free beams in this study. Using this relationship on the regular beams gave a RMSD of 0.0009 to our Monte Carlo calculated values. We have also investigated how the additional parameter $TPR_{10,5}$, together with $TPR_{20,10}$, can be used to more accurately predict $(\bar{L}/\rho)^{\mathrm{water}}_{\mathrm{air}}$. The model relating stopping-power ratios to this dual beam-quality specifier gave a RMSD of 0.0006 to Monte Carlo calculated ratios for all 24 beams used in this study. The relationship between $(\bar{L}/\rho)^{\mathrm{water}}_{\mathrm{air}}$ and $\%dd(10)_x$ proposed by Xiong and Rogers gave a RMSD of 0.0008 for the flattening filter free beams in this study and a RMSD of 0.0026 for conventional beams.

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