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Treatment vault shielding for a flattening filter-free medical linear accelerator

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Abstract

The requirements for shielding a treatment vault with a Varian Clinac 2100 medical linear accelerator operated both with and without the flattening filter were assessed. Basic shielding parameters, such as primary beam tenth-value layers (TVLs), patient scatter fractions, and wall scatter fractions, were calculated using Monte Carlo simulations of 6, 10 and 18 MV beams. Relative integral target current requirements were determined from treatment planning studies of several disease sites with, and without, the flattening filter. The flattened beam shielding data were compared to data published in NCRP Report No. 151, and the unflattened beam shielding data were presented relative to the NCRP data. Finally, the shielding requirements for a typical treatment vault were determined for a single-energy (6 MV) linac and a dual-energy (6 MV/ 18 MV) linac. With the exception of large-angle patient scatter fractions and wall scatter fractions, the vault shielding parameters were reduced when the flattening filter was removed. Much of this reduction was consistent with the reduced average energy of the FFF beams. Primary beam TVLs were reduced by 12%, on average, and small-angle scatter fractions were reduced by up to 30%. Head leakage was markedly reduced because less integral target current was required to deliver the target dose. For the treatment vault examined in the current study, removal of the flattening filter reduced the required thickness of the primary and secondary barriers by 10–20%, corresponding to 18 m^3 less concrete to shield the single-energy linac and 36 m^3 less concrete to shield the dual-energy linac. Thus, a shielding advantage was found when the linac was operated without the flattening filter. This translates into a reduction in occupational exposure and/or the cost and space of shielding.

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1. Introduction

A flattening filter-free (FFF) medical linac (Varian Clinac 2100; Varian Medical Systems, Palo Alto, CA) is expected to be commercially available soon. Such a linac, which is basically a standard linac with the flattening filter removed from the beam line, has been studied in detail for the delivery of stereotactic radiosurgery and radiotherapy, as well as intensity-modulated radiation therapy (IMRT) (O'Brien *et al* 1991, Fu *et al* 2004, Vassiliev *et al* 2006a, 2006b, 2006c, 2007, 2009, Pönisch *et al* 2006, Titt *et al* 2006a, 2006b, Kry *et al* 2007, 2008, Mesbahi 2007, Cashmore 2008). As expected, there are differences in the unflattened beam characteristics of FFF linacs and those of linacs with the flattening filter present (FF linacs). Of note, the FFF linac beam is softer; the central axis percent depth dose (PDD) in water for a 6 MV FFF beam resembles a 4 MV FF beam (Vassiliev *et al* 2006a). Additionally, the lateral dose profile is peaked on the central axis, and less integral target current is required to generate the same dose to the tumor (Vassiliev *et al* 2006b). As a result of these differences, the vault shielding parameters, such as the tenth-value layers (TVLs) and scatter fractions, calculated for flattened beams, may not be appropriate for shielding evaluations for unflattened beams. It must be determined if additional shielding would be required to use an FFF machine in a preexisting FF vault, or if less shielding could be employed in designing a vault for an FFF accelerator as compared to an FF accelerator, thereby saving space and shielding material. The current study evaluated these issues by first, calculating the basic vault shielding parameters for unflattened beams over the range of clinically useful energies, and second, by using these data to compare the vault shielding requirements for an FFF linac with those for an FF linac.

2. Methods

2.1. Basic parameters

The National Council on Radiation Protection and Measurements (NCRP) Report No. 151 provides general vault shielding guidelines for high-energy x-ray radiation therapy facilities (NCRP-151). Shielding design is particularly concerned with attenuation of the primary beam and stray radiation in the form of patient scatter, head leakage and wall scatter. Neutron production during high-energy irradiation must also be properly accounted for in the shielding design.

Primary beam attenuation, patient scatter, head leakage and wall scatter fractions were calculated both with and without the flattening filter by simulating 6, 10 and 18 MV beams using Monte Carlo. The Monte Carlo model used was of a Varian Clinac 2100 that had been previously developed with BEAMnrc and used to evaluate the attenuation (percent depth doses) and scatter characteristics (output factors) of both flattened and unflattened beams in water (Vassiliev *et al* 2006b). The impact that removal of the flattening filter has on neutron production was not calculated in the present study because it has already been reported (Kry *et al* 2007, 2008). To verify our methodology and results, we compared the values calculated with the flattening filter present to those published in NCRP Report No. 151. Although these values should be identical, some differences are expected between the two data sets because the NCRP values were calculated using a different Monte Carlo code and beam model and were sometimes subjected to conservative rounding. Because our goal was to provide FFF data relative to the NCRP data, and not relative to our own calculated FF data, we scaled our FF and FFF data equally so that the FF data matched the NCRP data.

2.1.1. Primary beam. The first TVL (TVL_1) and the equilibrium TVL (TVL_e) were calculated for an open 40×40 cm^2 primary beam impinging on a semi-infinite slab of Portland concrete.

Dose to concrete was tallied as a function of depth along the beam's central axis and, for consistency with the NCRP-151, corrected for beam divergence. The first and second TVL were calculated; the second TVL was used as the TVL_e.

2.1.2. Patient-scattered radiation. The patient scatter fraction was calculated using the approach described by Taylor *et al* (1999). Briefly, we impinged a 400 cm^2 primary field upon a cylindrical phantom with a 30 cm radius and calculated the kerma in water of the scattered radiation as a function of angle from the incident beam. The scatter fraction was calculated by normalizing the scattered kerma as a function of the scattering angle to the dose delivered to the depth of maximum dose in the cylindrical phantom. Also, the average energy of the scattered radiation was calculated as a function of the scattering angle. The average energy was then used to calculate the TVL of the scattered radiation by interpolating patient scatter TVLs as a function of energy (Tables B5a and B6 in NCRP Report No. 151).

2.1.3. Head leakage. The same TVL for head leakage was used with and without the flattening filter because the flattening filter produces or interacts with only a portion of head leakage. The amount of head leakage for the FF beams was assumed to be 0.1% of the useful beam (NCRP-151). For the FFF beams, this head leakage was scaled down by the amount that integral target current is reduced in order to deliver FFF treatments. This approach ignores the decrease in head leakage associated with removing a scattering source (the flattening filter) from the beam line, but is nevertheless a reasonable approximation: per unit dose on the central axis at 6 MV, the integral target current was reduced by 57% in the FFF mode (Vassiliev *et al* 2006b), while the head leakage in the patient plane was reduced by 58% (Cashmore 2008).

The relative integral target current requirements for FFF versus FF treatments were evaluated as follows. For IMRT (a primary focus with FFF), the amount of head leakage must be scaled by the 'IMRT factor' to account for increased head leakage with increased integral target current (equation 3.3 of NCRP Report No. 151). The NCRP-recommended value of 5 was used for the FF case. However, for the FFF beams, the target current requires further attention. Both the relative number of monitor units (MUs) required to deliver a treatment and the integral target current required to produce 1 MU are different for the FFF and FF beams. As a further complication, for the FFF beam, the relative number of MUs required to deliver a treatment depends on field size because the FFF beam intensity decreases with increasing distance from the central axis. Therefore, rather than scaling simply by the IMRT workload factor of 5, we developed a new correction factor (IMRT FFF factor, C_{IF}) to account for these differences that was determined for each energy:

$$C_{IF} = \left(\frac{MU_{FF\,IMRT}}{MU_{FF\,conv}}\right)\left(\frac{\text{MU per treatment}_{FFF}}{\text{MU per treatment}_{FF}}\right)\left(\frac{\text{Target current per MU}_{FFF}}{\text{Target current per MU}_{FF}}\right). \quad (1)$$

The first term of equation (1) is from the NCRP Report No. 151 to account for IMRT and was 5 regardless of the presence of the flattening filter. The second term accounts for the difference in MUs required to deliver FF versus FFF treatments and is treatment site dependent. The third term accounts for the fact that a different integral target current is required to produce 1 MU when the flattening filter is removed. The second term was calculated as the average value from treatment planning studies of radiation therapy for prostate, lung, spine, liver and head and neck cancer both with and without the flattening filter at 6 and 18 MV (Vassiliev *et al* 2006c, 2007, 2009). For each disease site, comparable treatment plans were generated with or without the flattening filter, and the relative number of MUs required was determined. The third term of equation (1) was taken from our previous Monte Carlo study (Vassiliev *et al* 2006b).

Table 1. Primary barrier TVLs (cm) for ordinary concrete. Flattening filter (FF) data were obtained from NCRP Report No. 151 and flattening filter-free (FFF) data were scaled relative to the NCRP values.

Nominal energy		FF	FFF
6 MV	TVL_1	37	30
	TVL_e	33	27
10 MV	TVL_1	41	36
	TVL_e	37	36
18 MV	TVL_1	45	39
	TVL_e	43	40

2.1.4. Wall-scattered radiation. We calculated the wall scatter fraction by impinging a radiation field on ordinary concrete (at normal incidence and at 45° incidence) and tallying the relative beam intensity as a function of the angle from the normal. This was done for both flattened and unflattened beams at all three energies.

2.1.5. Neutron production. Neutron source strength and fluence were measured previously for a FFF linac operated at 18 MV (Kry *et al* 2008). The fluence per MU determined previously was scaled by the relative number of MUs required to deliver high-energy radiation therapy without the flattening filter.

2.2. Vault shielding example

To evaluate the impact of the FFF shielding parameters calculated above, we calculated the vault shielding requirements for the FF and FFF modes assuming 100% IMRT usage for each. The treatment vault dimensions, wall use factors, occupancy factors and controlled status of relevant areas were taken from the vault shielding example presented in chapter 7 of NCRP Report No. 151. The vault shielding requirements were evaluated for four scenarios: a dedicated single-energy (6 MV) linac operated (1) exclusively with the flattening filter and (2) exclusively without it; a dual-energy (6 MV/18 MV) linac operated (3) exclusively with the flattening filter and (4) exclusively without it. The single-energy linac was assumed to have a weekly workload of 450 Gy, and the dual-energy linac was assumed to have weekly workloads of 250 Gy at each energy.

3. Results

3.1. Basic parameters

3.1.1. Primary beam. The TVL_1 and TVL_e calculated for the FF beam were consistent with those published in the NCRP Report No. 151; the average disagreement for all energies was 9%. The TVLs for the FFF beams were scaled by these differences. The scaled FFF TVLs and the NCRP data are shown in table 1. For all energies, the TVLs for the FFF beams were smaller than those for the FF beams. On average, the reduction was 12%.

3.1.2. Patient-scattered radiation. The patient scatter fractions calculated for the FF beam were generally within 30% of the values calculated by Taylor *et al* (1999). Table 2 shows the scaled FFF patient scatter fractions and the NCRP patient scatter fractions for FF beams. The patient scatter fractions are markedly smaller for the FFF beams at small scatter angles (⩽60°),

Table 2. Scatter fractions (α) at 1 m from a human-size phantom, target-to-phantom distance of 1 m and field size 400 cm^2. Flattening filter (FF) data were obtained from NCRP Report No. 151 and flattening filter-free (FFF) data were scaled relative to the NCRP values.

Angle (degrees)	6 MV		10 MV		18 MV	
	FF	FFF	FF	FFF	FF	FFF
10	1.04×10^{-2}	8.07×10^{-3}	1.66×10^{-2}	1.16×10^{-2}	1.42×10^{-2}	9.63×10^{-3}
20	6.73×10^{-3}	5.59×10^{-3}	5.79×10^{-3}	4.43×10^{-3}	5.39×10^{-3}	4.03×10^{-3}
30	2.77×10^{-3}	2.44×10^{-3}	3.18×10^{-3}	2.63×10^{-3}	2.53×10^{-3}	1.65×10^{-3}
45	1.39×10^{-3}	1.30×10^{-3}	1.35×10^{-3}	1.20×10^{-3}	8.64×10^{-4}	7.36×10^{-4}
60	8.24×10^{-4}	8.12×10^{-4}	7.46×10^{-4}	6.86×10^{-4}	4.24×10^{-4}	4.00×10^{-4}
90	4.26×10^{-4}	4.46×10^{-4}	3.81×10^{-4}	4.03×10^{-4}	1.89×10^{-4}	1.93×10^{-4}
135	3.00×10^{-4}	3.42×10^{-4}	3.02×10^{-4}	3.82×10^{-4}	1.24×10^{-4}	1.41×10^{-4}
150	2.87×10^{-4}	3.32×10^{-4}	2.74×10^{-4}	3.47×10^{-4}	1.20×10^{-4}	1.25×10^{-4}

Table 3. TVLs in concrete (cm) for patient-scattered radiation at various scatter angles. Flattening filter (FF) data were obtained from NCRP Report No. 151 and flattening filter-free (FFF) data were scaled relative to the NCRP values.

Angle (degrees)	6 MV		10 MV		18 MV	
	FF	FFF	FF	FFF	FF	FFF
15	34	29	39	32	44	41
30	26	24	28	27	32	28
45	23	20	25	22	27	24
60	21	18	22	20	23	21
90	17	16	18	17	19	17
135	15	16	15	16	15	16

but slightly larger at large scatter angles (>60°). The TVLs for patient-scattered radiation are shown in table 3 for each scattering angle and nominal beam energy. The average energy for the patient-scattered radiation was, on average, 20% lower when the filter was absent. This corresponded to a TVL that was, on average, 7% smaller. This reduction in patient scatter TVL was consistent with the reduction in beam energy associated with removal of the flattening filter; that is, the 6 MV FFF TVL was very similar to the 4 MV FF TVL.

3.1.3. Head leakage. Removal of the flattening filter reduced head leakage parameters by reducing integral target current requirements. The specific values for equation (1) can be evaluated in either of two ways depending on the calibration of the linac. First, if the FF and FFF modes are each clinically calibrated such that 1 MU equals 1 cGy at d_{max} on the central axis, then the relative MU per treatment (FFF/FF) is 1.11 and 1.40 at 6 and 18 MV respectively based on treatment planning studies. That is, 11% or 40% more MUs are required in the FFF mode. However, the relative integral target current to produce 1 MU under these calibration conditions was previously found to be 0.43 and 0.18 at 6 and 18 MV respectively (Vassiliev *et al* 2006b). While this first calibration is most clinically reasonable, studies in the literature have often not recalibrated the MU for FFF mode (Vassiliev *et al* 2007). Thus, a much higher dose is delivered on the central axis per MU. Under this second scenario, the relative MU per treatment (FFF/FF) was reduced, being 0.54 at 6 MV and 0.38 at 18 MV. In this case though, the integral target current to produce 1 MU (FFF/FF) was 0.90 at 6 MV and 0.67 at 18 MV (Vassiliev *et al* 2006b).

Table 4. Differential dose albedo (wall-reflection coefficient), $\times 10^{-3}$, for normal incidence on ordinary concrete. Angle of reflection is measured in degrees from the normal. Flattening filter (FF) data were obtained from NCRP Report No. 151 and flattening filter-free (FFF) data were scaled relative to the NCRP values.

Angle of reflection	6 MV		10 MV		18 MV	
	FF	FFF	FF	FFF	FF	FFF
0	5.3	6.6	4.3	6.8	3.4	4.8
30	5.2	6.5	4.1	6.5	3.4	4.8
45	4.7	5.8	3.8	6.0	3.0	4.2
60	4.0	5.0	3.1	4.9	2.5	3.5
75	2.7	3.5	2.1	3.3	1.6	2.3

Table 5. Differential dose albedo (wall-reflection coefficient), $\times 10^{-3}$, for 45° incidence on ordinary concrete. Angle of reflection is measured in degrees from the wall normal. Flattening filter (FF) data were obtained from NCRP Report No. 151 and flattening filter-free (FFF) data were scaled relative to the NCRP values.

Angle of reflection	6 MV		10 MV		18 MV	
	FF	FFF	FF	FFF	FF	FFF
0	6.4	8.3	5.1	7.3	4.5	6.1
30	7.1	8.8	5.7	8.0	4.6	6.1
45	7.3	9.1	5.8	8.1	4.6	6.1
60	7.7	9.6	6.0	8.2	4.3	5.7
75	8.0	9.8	6.0	8.2	4.0	5.3

Regardless of an approach, the IMRT factor (C_{IF}) was 5 with the filter in place, but for FFF the C_{IF} value was 2.4 for 6 MV and 1.3 for 18 MV. That is, the integral target current was reduced by one-half to three quarters in the FFF mode.

3.1.4. Wall-scattered radiation. The scaled FFF and NCRP wall scatter fractions are shown in table 4 (at normal incidence) and table 5 (at 45° incidence). As shown, wall scatter fractions increased, on average, by 40% when the flattening filter was absent. The increase in wall scatter fraction for the FFF beams was consistent with the decreased beam energy; that is, 6 MV FFF wall scatter factors were very similar to 4 MV FF wall scatter factors.

3.1.5. Neutron production. As outlined in the head leakage section, the relative number of MUs required to deliver 18 MV FFF treatments was only 0.38 of that required to deliver 18 MV FF treatments when the MU was not renormalized. Using published neutron fluences per MU (Kry *et al* 2008), we found that the total number of neutrons was reduced by a factor of 3.7 when the flattening filter was removed.

3.2. Vault shielding example

Following the numeric example provided in NCRP Report No. 151, less concrete was required to achieve the same vault shielding objectives for a linac operated in the FFF mode than in the FF mode for both the single-energy and dual-energy linacs. For the single-energy linac, the primary barrier was approximately 20% thinner (100–120 cm versus 125–150 cm of concrete (depending on specific location)) and the secondary barriers were ∼10% thinner (∼80 cm versus 90 cm of concrete). The vault's four walls required a total of 18 m^3 less concrete to shield the linac, and the shielding footprint was 4.4 m^2 (47 ft^2) smaller. For the dual-energy linac, the primary barrier was ∼9% thinner (∼150 cm versus 165 cm of concrete) and the secondary barriers were approximately 20% thinner (∼90 cm versus 115 cm of concrete). The required door shielding for the dual-energy linac was also reduced, by 71%, when the flattening filter was removed. The vault's four walls required a total of 36 m^3 less concrete to shield the linac, and the shielding footprint was 8.5 m^2 (92 ft^2) smaller.

4. Discussion

Vault shielding parameters were generally smaller for the same electron accelerating energy when the filter was removed from the beam line. This is not surprising as removal of the flattening filter resulted in a softer spectrum. In water, the 6 MV FFF beam had a depth dose similar to a 4 MV FF beam (Vassiliev *et al* 2006a). In the current study, patient scatter TVLs and wall scatter factors from the 6 MV FFF beam were also similar to a 4 MV FF beam. However, the first and equilibrium TVLs of the primary 6 MV FFF beam were dissimilar to a 4 MV FF beam in concrete due to differences in the beam spectra and effective Z of concrete versus water. These properties of FFF beams call into question the FFF nomenclature that has been used historically, where the beam is named based on electron accelerating energy to be consistent with the FF beam. Users of the data in tables 1–5 must be alert to potential changes in FFF nomenclature.

The primary beam TVLs were smaller for the FFF beams than for the FF beams because the FFF beams were softer (Vassiliev *et al* 2006b) and also because of the shape of the beam. FF beams have a broad flat lateral profile and will therefore not lose intensity on the central axis due to scatter. In contrast, the FFF beam is forward peaked along the central axis and, consequently, will lose intensity along the central axis due to scatter to the less intense periphery of the radiation field. Patient scatter fractions were also generally smaller for the FFF beams than for the FF beams, which at first seems counterintuitive because the FFF beam has a lower energy. The first reason that patient scatter fractions were smaller for the FFF beams is that although the softer beam was scattered more, it was also attenuated more by the large cylindrical phantom through which the scatter must penetrate. The second reason is that the patient scatter term also includes collimator scatter, including scatter from the flattening filter. With the flattening filter removed the collimator scatter, and therefore the patient scatter term, is reduced. For large-angle patient scatter and for wall scatter, the scattered radiation did not need to penetrate a phantom (or needed to penetrate less material); therefore, due to the softer spectrum, the scatter fractions were larger when the flattening filter was removed. However, it is worth noting that large-angle patient scatter and wall scatter generally play a minimal role in vault shielding.

Examining the vault shielding examples, we found that both primary and secondary barrier thicknesses were reduced with the FFF beams. The primary barrier requirements were reduced because of the reduced TVL for the primary FFF beam. The secondary barrier requirements were reduced because of the more efficient delivery of dose with the FFF beam. Secondary barrier requirements were dominated by head leakage, and the barrier reduction therefore corresponded to the reduction in the integral target current to deliver treatments with FFF beams.

In the vault shielding example, we have assumed that the electron accelerating energy was not changed when the filter was removed. This results in a softer spectrum and an expected decrease in shielding requirements. One can imagine increasing the electron accelerating potential of the FFF beam in order to produce a percent depth dose (PDD) on the central axis in water comparable to an FF beam. For example, an 8 MV FFF beam has similar central axis beam characteristics in water as a 6 MV FF beam (Vassiliev *et al* 2006d). Interpolating from the data in tables 1–5 and the C_{IF} values calculated in this study, the shielding requirements for the treatment vault were calculated for an 8 MV FFF beam. As compared to a 6 MV FF beam, the 8 MV FFF primary barrier was slightly reduced, by approximately 7%. Although the 8 MV FFF beam had a similar central axis PDD in water as compared to the 6 MV FF beam, the softer spectrum was more attenuated in the higher Z concrete and therefore less primary barrier is required. Secondary barriers were reduced by approximately 11% for the 8 MV FFF beam as compared to 6 MV FF due to decreased integral target current requirements. The shielding advantage realized with the 8 MV FFF beam compared to the 6 MV FF beam (7–11%) is slightly less than was observed when comparing the 6 MV FFF beam to the 6 MV FF (10–20%), but still offers a shielding advantage.

The shielding advantage of the FFF beam naturally depends on the treatment energy used, which depends on the clinical implementation of the FFF machine. If a purely FFF machine is used, it is reasonable to imagine increasing the electron energy to ∼8 MeV so the PDD characteristics are most similar to the standard 6 MV. In this case, the FFF machine would offer a modest shielding advantage of 7–11%. Alternately, and more likely, the FFF Varian Clinac will have the capacity to operate in both an FFF and an FF mode. Because there are a limited number of energy switches, the electron energy would be unlikely to change between 6 MV FF and 6 MV FFF modes. In such a case, or in any scenario when the electron energy is not increased, the shielding advantage from the FFF mode would be 10–20%. Naturally, if a linac were operated in both FF and FFF modes, a shielding evaluation would need to account for estimated workloads in both modes, and appropriately shield for both FF and FFF beams. Of importance, this work demonstrates that based on either implementation of an FFF machine, it is likely that any established vault that operates with an FF linac can also operate with an FFF linac with no changes required in shielding.

Future shielding requirements should also be considered when evaluating the shielding for an FFF linac, specifically in regard to the instantaneous dose rate. A clinical advantage of the FFF linac over the conventional FF linac is the former's ability to greatly increase the dose rate, by a factor of 2.1 and 3.7 on the central axis at 6 and 18 MV respectively (Vassiliev *et al* 2006a). Currently, the NCRP defines the instantaneous dose rate such that it applies to any given hour of treatment (NCRP-151). As a result, this requirement does not affect FFF shielding any differently than FF (as long as the same number of patients are treatment per hour). However, if regulations were changed to restrict the time scale of the instantaneous dose rate, this could affect the shielding requirements (or operation) of an FFF accelerator. Nevertheless, based on current regulations, there are substantial savings in the amount of shielding material and floor space usage required when operating a linac without the flattening filter.

5. Conclusions

By providing the vault shielding data for FFF linacs, this study enables medical physicists to perform the appropriate shielding calculations to accommodate such linacs. By removing the flattening filter from the linac, the vault's shielding burden was reduced for reasonable clinical usage. This finding has several implications. First, it is likely that any established vault that operates with an FF linac can also operate with an FFF linac with no changes required in shielding. Second, the amount of concrete and floor space required to meet vault shielding guidelines could be reduced for FFF linacs relative to FF. Alternately, if a treatment vault design is consistent with FF shielding requirements, using an FFF linac will decrease the occupational exposure, which is consistent with the ALARA principle. Thus, an FFF linac has several advantages over a traditional FF linac.

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