Reducing electron contamination for photon beam-quality specification

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The percentage depth dose at 10 cm in a 10×10-cm^2 photon beam at an SSD of 100 cm, %dd(10), is a better beam-quality specifier for radiotherapy beams than the commonly used values of TPR_{10}^{20} or nominal accelerating potential. The presence of electron contamination affects the measurement of %dd(10) but can be removed by the use of a 0.1-cm lead filter, which reduces surface dose from contaminant electrons from the accelerator by more than 95% for radiotherapy beams with energies from ^{60}Co to 50 MV. The filter performs best when it is placed immediately below the head. An electron-contamination correction factor is introduced to correct for electron contamination from the filter and air. It converts the %dd(10) which includes the electron contamination with the filter in place [hereafter $\%dd(10)_m$], into %dd(10) for just the photons in the filtered beam. The correction factor is a linear function of $\%dd(10)_m$ for all filtered beams with $\%dd(10)_m > 70\%$. A small correction for the photon filtering effect converts the pure photon %dd(10) for the filtered beam into that for the unfiltered beam, which can be used to determine stopping-power ratio. Calculations show that the values of water-to-air stopping power ratio in the unfiltered beam are related to the values of $\%dd(10)_m$ in the filtered beam by a cubic function. The uncertainty of stopping-power ratios in unfiltered beams for the same value of the $\%dd(10)_m$ is within 0.2% for all beams.

I. INTRODUCTION

A beam-quality specifier is necessary in the implementation of most clinical dosimetry protocols in order to select various parameters.[1,2] The quality of a radiotherapy x-ray beam is related to (i) the energy of the accelerated electrons, (ii) the thickness and atomic number of the target, (iii) the effect of added filtration, and (iv) the design of the beam defining system. This implies that the commonly used value of nominal accelerating potential (NAP) is not a sufficient specification for megavoltage x-ray beams. Clinical dosimetry protocols usually specify beam quality by the value of TPR_{10}^{20}, which is determined by measuring the absorbed dose on the beam axis at depths of 20 and 10 cm for a constant source–detector distance and for a 10×10-cm field at the plane of the chamber. The value of TPR_{10}^{20} can be directly related to the stopping-power ratios needed in dose calculations.[3,4] However, it has been shown that stopping-power ratios vary by up to 1.5% for bremsstrahlung beams with the same value of TPR_{10}^{20},[5,6] and experimental results demonstrate variations of up to 1% for thick-target bremsstrahlung beams.[7]

LaRiviere and Kosunen and Rogers argued that %dd(10), the percentage depth-dose at 10-cm depth in a 10×10-cm^2 photon beam at an SSD of 100 cm, is a better beam quality specifier for radiotherapy photon beams than TPR_{10}^{20} or NAP.[6,8] Compared with TPR_{10}^{20} and NAP, %dd(10) is: (i) a better indicator of a unique stopping-power ratio; (ii) more sensitive to beam-quality changes for high-energy beams; and (iii) more intuitively meaningful.

LaRiviere[8] showed that the value of %dd(10) is a good indicator of the NAP and proposed that the beam quality (Q) in MV should be specified in terms of %dd(10) with

$$Q = 10^{(\%dd(10)-46.78)/26.09} \quad [\mathrm{MV}]. \tag{1}$$

He concluded that beam quality in MV should be specified using Eq. (1), but in practice his method amounts to using %dd(10) as the beam-quality specifier.

Kosunen and Rogers have done an extensive series of Monte Carlo calculations for many different clinical and other realistic bremsstrahlung spectra.[6] They confirmed the variation in stopping-power ratio for a given TPR_{10}^{20} value as reported by Andreo.[5] In addition, for all thick-target bremsstrahlung beams, they found a linear relationship between the calculated pure photon %dd(10) values and the water to air stopping-power ratios; i.e.,

$$\left(\frac{\bar{L}}{\rho}\right)_{\mathrm{air}}^{\mathrm{water}} = 1.2676 - 0.002224[\%dd(10)]. \tag{2}$$

They pointed out that %dd(10) specifies stopping-power ratios within 0.2% compared with variations of up to 0.7% for different thick-target bremsstrahlung beams with the same value of TPR_{10}^{20}. Figure 1, showing this well-defined linear relationship, is the key result of that study. They concluded that %dd(10), as a well-defined and easily measured quantity, can be directly used as a beam-quality specifier. Additional values of the water-to-air stopping-power ratio and %dd(10) for the calibration beams of the National Physical Laboratory (U.K.) are included in Fig. 1 (based on accelerator information supplied by B. Owen, NPL, 1993). The NPL datapoints are consistent with the fitted straight line within the maximum deviation of 0.2% for $\%dd(10) \geq 63\%$ and follow a unique trend line below that.

The major complication with the measurement of %dd(10) is electron contamination which affects the maximum dose.[9–12] Karlsson *et al.*[13] reported that electron contamination also affects the dose at 10-cm depth for very high-energy photon beams and in turn affects TPR_{10}^{20}. Kosunen and Rogers reported that their calculated %dd(10) values were generally ~2% higher than the measured values for high-energy photon beams due to the effects of contaminant electrons at dose maximum in the measured beam. These contaminant electrons can originate in source hardware, beam collimators, filters, shaping blocks and their sup-

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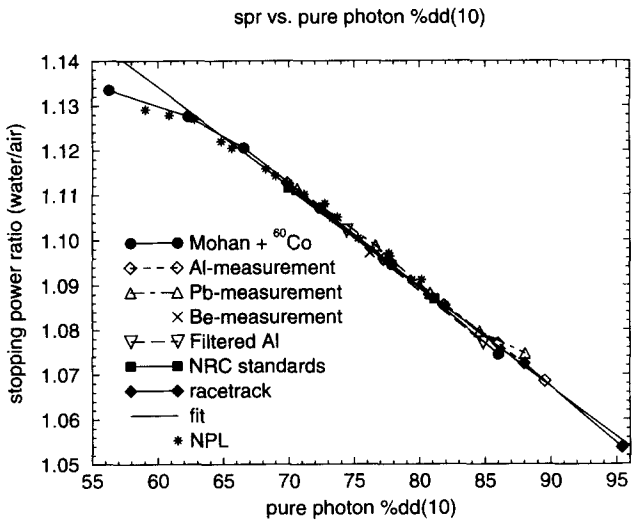

FIG. 1. Calculated water to air stopping-power ratios (based on ICRU 37 stopping powers) versus pure photon percentage depth dose at 10 cm in a 100-cm^2 field at SSD=100 cm for the spectra considered here. The straight line shown is the linear fit to all the bremsstrahlung beams given by Eq. (2) with an rms deviation of 0.0012 and a maximum deviation of 0.003. Redrawn from Ref. 6 except the data points for NPL, which are calculated presently using the accelerator data provided by B. Owen of NPL.

porting tray, and the air through which the beam passes. Such electron contamination tends to reduce or eliminate the so-called "skin-sparing" advantage of megavoltage photon beams for radiotherapy.[14–17] Improvements in beam purity and skin sparing can be achieved through: (i) reduction in beam size to allow electrons to scatter out,[18,19] (ii) magnetic removal of electrons,[20,21] (iii) use of medium-to-high-Z filters that scatter contaminant electrons out of the beam without generating appreciable additional electrons,[22–26] and/or (iv) replacing the air the beam passes through by helium in a thin plastic bag.[27–30] Several studies have shown that using an electron filter is an effective and simple way to reduce electron contamination.[23,31–34] Ling and Biggs reported that a 0.55-g/cm^2-thick lead foil was an optimal electron filter for a 25-MV linac.[23] They also pointed out that lead was the overall best material for the purpose of filtering secondary electrons. From a study of three 10-MV accelerators, Rao *et al.* showed that Pb can be used as an effective filter material for field sizes up to 30×30 cm^2 (see Ref. 26). A Monte Carlo calculation of electron contamination in a ^{60}Co therapy beam was done by Rogers *et al.*[33] They reported that a 0.075-cm-thick copper filter, placed immediately behind the head, creates a considerable reduction in electron contamination. For a 6-MV linac, Parthasaradhi *et al.* observed that the electron contamination of both the open beam and the beam with the tray can be effectively reduced by placing a lead filter immediately below the blocking tray, which was located at a distance of 61.5 cm from the source.[34] They noticed that the differences in percentage depth dose between the open and the filtered beam were less than 2%.

Kosunen and Rogers pointed out that a 0.1-cm-thick lead foil placed at the exit of the accelerator head completely eliminated the effects of any upstream electron contamination.[6] The primary reason that filters reduce electron contamination is that they scatter the electrons, thereby removing most contaminant electrons from the beam and similarly spreading any electrons generated in the filter over a wide area. The filter also fully stops low-energy contaminant electrons. Thus the lead filters should be thick enough to make negligible the effects of contaminant electrons generated upstream. In this case only those electrons generated by photon interactions in the air past the filter and in the filter itself contribute to the electron contamination. At the same time, the filters can be sufficiently thin that: (i) the photon beam quality is little affected, (ii) the photon dose is reduced by just a few percent, and (iii) the electron contamination generated in the filters themselves is minimized.

The present work is a further study of high-energy beam-quality specification with emphasis on the reduction of electron contamination. Our central aim is to calculate a correction to %dd(10) measured with the filter in place for the residual electron contamination from the filter and air. This correction will be independent of the initial contamination and thus applicable without knowledge of the accelerator electron contamination. The optimal position and thickness of the lead filter is studied. Our calculations show that using thin higher-Z (lead) filters can substantially reduce the electron contamination and just slightly affect the photon beam quality. This latter effect can be easily corrected for. It is found that, for a filtered radiotherapy beam, the electron contamination has a very small effect on %dd(10) (1% for Mohan *et al.*'s 24-MV beam) and the uncertainty introduced in the stopping-power ratio becomes subsequently as small as 0.2%.

II. MONTE CARLO CALCULATIONS

The EGS4 Monte Carlo code system[35] with the default PRESTA algorithm for electron transport[36] was used. The NRCC user-code DOSRZ uses the Monte Carlo technique to calculate energy deposition in an arbitrary cylindrical geometry for electron or photon beams incident in a wide variety of configurations. The code has been benchmarked against a large amount of experimental data (see Ref. 37 and references therein). This code was used to calculate central-axis depth-dose curves for photon beams incident either directly on a 30-cm-thick water phantom or on a filter of arbitrary thickness and material at some distance away from the phantom with air between the filter and the phantom. The code was modified slightly to keep track separately of the dose from the photons or electrons incident on the water phantom. The values of %dd(10) were calculated for a variety of input photon spectra. Most of these spectra were taken from the previous study[6] and are briefly described below. All the Monte Carlo calculations were done for a point source 100 cm from the surface of the water and with a 100-cm^2 field size at the surface of the water phantom. The Monte Carlo calculations were done for a sufficient number of histories to reduce the statistical uncertainty on the photon dose in individual depth bins to a few tenths of a percent or less and to a few percent on the dose due to the incident (contaminant) electrons.

The EGS4 transport parameters AE, the lowest energy at which secondary electrons can be created, and ECUT, the

minimum energy for electron transport,[35,38] were 521 keV (which includes the electron rest mass), and PCUT and AP, the photon equivalents of ECUT and AE, were 10 keV.

The code DDSPR[39] uses precomputed data for monoenergetic photon beams and folds these data with arbitrary photon spectra to calculate depth-dose curves and stopping-power ratios as a function of depth. DDSPR was used to calculate the values of the water to air stopping-power ratios. They are for 100-cm^2 photon beams and are at a depth of 10 cm. There is very little depth dependence of the stopping-power ratio past dose maximum. The input photon spectra for the DDSPR code were the same input spectra as used with the DOSRZ code plus these spectra after passing through various filters and thicknesses of air. These filtered spectra were calculated using the NRCC EGS4 Monte Carlo user-code ACCEL which was used previously.[6]

A variety of input photon spectra was used in the calculations.[6] "Mohan" spectra are the typical clinical linac spectra calculated by Mohan *et al.*[40] "Al-measurement," "Pb-measurement," and "Be-measurement" spectra are the measured spectra generated by 10-, 15-, 20-, 25-, and 30-MeV beams of electrons incident on thick targets of aluminum, lead and beryllium, respectively.[41,42] "Filtered Al" represents the spectra obtained by starting from the 10- and 20-MV- thick target aluminum spectra and analytically filtering these by an additional 14 cm of aluminum. "NRC standards" denotes the spectra used for standards work at NRC, which are generated by a thick target of aluminum and flattened by two different conical aluminum flattening filters. The "racetrack" beams are 30- and 50-MV beams from the Scanditronix 50-MV racetrack microtron. The ^{60}Co spectrum includes a 30% fluence contribution from photons scattered from the source capsule and collimators.[33] For more details of these input spectra, see the Appendix of Ref. 6. The NPL spectra are calculated with the Monte Carlo code ACCEL based on the accelerator geometries provided by Owen (private communication, NPL, 1993).

In these calculations the effects of photo-nuclear reactions [(γ,p) and (γ,n)] are ignored. In water the cross section for the (γ,p) reaction is larger than that for (γ,n) reactions which will be ignored because any dose delivered requires the neutrons to interact, thus eliminating the local effect almost completely.[37,43] As for neutrons from the accelerator itself, Ing and Shore have shown that the neutron dose is less than 0.1% of the photon dose.[44] For the (γ,p) reactions, the protons deposit their dose locally. At the peak of the giant resonance in water (24 MeV) the (γ,p) cross section is about 4% of the total cross section and thus could contribute a significant amount to the dose (although it is problematic whether ion chambers would be sensitive to this dose). However, to first order, this dose is proportional to the photon fluence which is also proportional to the photon dose (past d_{max}). Thus, even if it is measured, the proton dose does not affect %dd(10). This cancellation will not be perfect, but taking into account that the vast majority of the photon dose comes from photons with energies much below 24 MeV, the effect is negligible, except possibly for 50-MV beams.

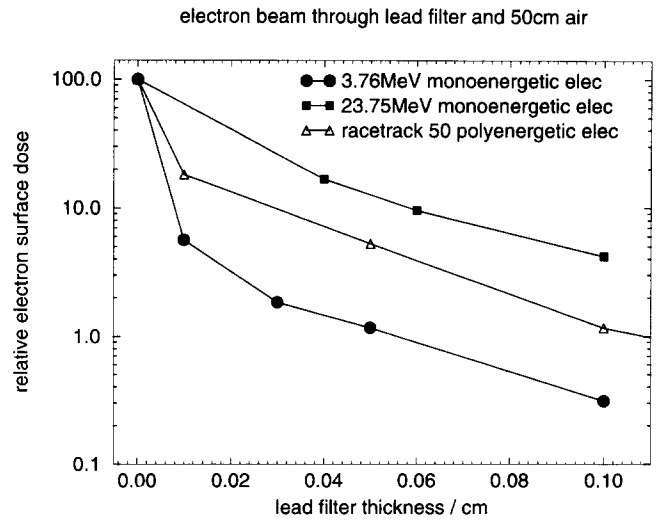

FIG. 2. The relative electron dose in the first 2 mm of a water phantom versus the thickness of the lead filter calculated for 100-cm^2 electron beams at an SSD of 100-cm traversing various lead filters and 50 cm of air past the filter. The 3.76 (23.75)-MeV monoenergetic electrons are recoil electrons with the maximum energy in a 4 (24)-MV spectrum while the polyenergetic beam is the calculated electron contamination generated by the target in a racetrack 50-MV photon beam.

III. RESULTS AND DISCUSSION

A. The effect of filters

To see how effectively the filters remove the upstream electrons, we have done calculations for electron beams traversing various lead filters and the air past the filters. Figure 2 plots the relative electron surface dose scored in the first 0.2 cm of a water phantom versus the thickness of the lead filter. The calculations are for 3.76- and 23.75-MeV monoenergetic electron beams and for a polyenergetic electron beam which is the secondary electron beam obtained from the Monte Carlo calculation of a 50-MeV electron beam traversing a thick tungsten/copper target and 100 cm of air. The polyenergetic beam is an approximation of the electron contamination in a racetrack-50-MV photon beam. The value of 3.76 (23.75) MeV is the maximum energy of recoil electrons in a 4 (24)-MV spectrum. It is seen from Fig. 2 that a 0.1-cm lead filter reduces the contaminant electron surface dose to a few percent or less of its unfiltered value for whole range of the radiotherapy beams (up to 50 MV). Other calculations for photon beams from ^{60}Co to 50 MV show that a 0.1-cm lead filter reduces the photon dose maximum by approximately 5% except for ^{60}Co beams for which the reduction is 8%. The present calculated dose reduction is generally consistent with the measurements done by Ling and Biggs[23] if one considers the mean energy of the electrons in the photon spectrum when using Fig. 2.

Calculations were done for foils of different materials to determine the best choice of filter material for reducing electron contamination. Al, Fe, Cu, Zn, Sn, W, and Pb were considered. Figure 3 shows the relative electron surface dose, normalized to the electron surface dose with only 50 cm of air in place (i.e., no foil), versus atomic number of the filter material, calculated for an incident 23.75-MeV monoener-

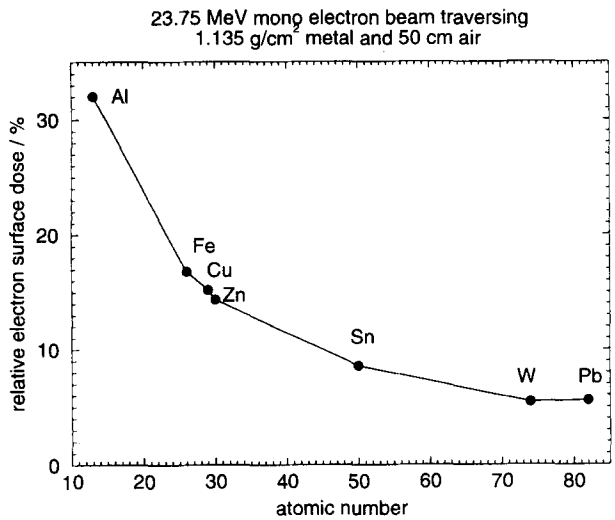

FIG. 3. The relative electron dose in the first 2 mm of a water phantom versus the atomic number of the filter material, calculated for 23.75 MeV monoenergetic 100 cm^2 electron beams at an SSD of 100-cm traversing various filters with the same thickness of 1.13 g/cm^2 and 50 cm of air past the filters. Al, Fe, Cu, Zn, Sn, W, and Pb are considered. The y-axis value is normalized to the electron surface dose for 50 cm of air without the metal foil in place.

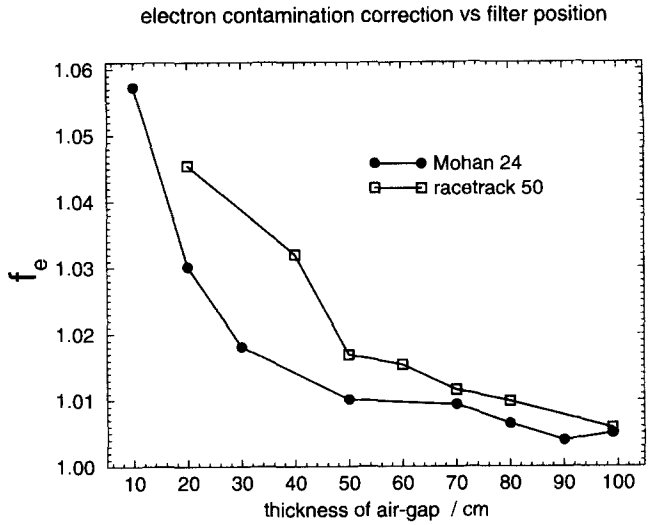

FIG. 4. The electron contamination, generated in a 0.1-cm lead filter and the various air gaps past the filter vs the distance of the filter from the surface of the water phantom, i.e., the thickness of the air gap. The calculations are for two filtered photon beams at an SSD of 100 cm with a field size of 100 cm^2. f_e is defined to convert the %dd(10) which includes electron contamination to the %dd(10) for just photons in the filtered beam. The optimal location of filter is at the position immediately behind the accelerator head.

getic electron beam traversing a 1.13 g/cm^2 foil. Materials with atomic numbers greater than that for Sn are good choices of the filter material for high-energy photon beams since the filters of these materials reduce electron dose considerably (by more than 90% of its unfiltered value for the filters of 1.13 g/cm^2 thickness in a 23.75-MeV monoenergetic electron beam).

To correct quantitatively for the remaining electron contamination from photon interactions in the filter or the air past the filter, we define a correction factor, f_e, for the filtered beam as

$$f_e = \left(1 - \frac{D^e_{10}}{D^{\text{tot}}_{10}}\right) \Big/ \left(1 - \frac{D^e_{\max}}{D^{\text{tot}}_{\max}}\right), \tag{3}$$

where D^e_{10} and $D^e_{\max}$ are the doses, respectively, due to contaminant electrons at 10-cm depth and at the depth for the maximum *total* dose, $d_{\max}$, while D^{tot}_{10} and $D^{\text{tot}}_{\max}$ are the total doses, respectively, at 10-cm depth and $d_{\max}$. The factor f_e converts the %dd(10) which includes electron contamination generated in the filter and the air past the filter [i.e., 100 $D^{\text{tot}}_{10}/D^{\text{tot}}_{\max}$] into %dd(10) for just the photon component of the filtered beams [i.e., $100\,(D^{\text{tot}}_{10} - D^e_{10})/(D^{\text{tot}}_{\max} - D^e_{\max})$]. For more details about f_e, see Sec. III B. A calculation for the Mohan 24-MV spectrum traversing a 1.13 g/cm^2 filter and 50 cm of air past the filter indicates that the value of f_e varies from 1.0099 to 1.0105 for filter materials from Sn to Pb. It is concluded that lead remains the best choice of the filter material since it most strongly reduces contaminant electrons from the accelerator, and the amount of electron contamination it generates is comparable to that of other materials.

We have calculated the electron contamination generated in a 0.1-cm lead filter as well as the air gap past the filter, as a function of the distance of the filter from the surface of the water phantom, i.e., the thickness of the air gap. Figure 4 shows that the calculated values of f_e decrease as the thickness of the air gap increases for the Mohan 24-MV and racetrack 50-MV spectra. To isolate the contaminant contribution from air, we have done calculations with no filter in place and find values of $D^e_{\max}/D^{\text{tot}}_{\max}$ are in the range of 0.02%–0.03% for photon energies from ^{60}Co to 50 MV for 50-cm of air, i.e., the air generates very few contaminant electrons in this 100-cm^2 field. The increase in electron contamination when the filter is closer to the water phantom is because the electrons generated in the filter are not as spread out by the time they reach the water surface. Figure 4 suggests that the filter should be located as close to the source as possible. However, filters close to the source do not remove the electrons generated in the outer collimators or those generated in the air above the filters. An optimal location, at which the filter can remove all electrons from the head and can broadly scatter those generated in the filter by the time they reach the water surface, is the position immediately behind the head. This agrees with the measurement done by Parthasaradhi *et al.*[34] A position of 50 cm away from phantom surface is recommended in practice and is considered for the following detailed calculations. For those accelerators for which the 50-cm position is not achievable, an approximate correction can be made based on the information in Fig. 4.

1. The effect of the lead filter on photon beam quality

The present calculations show that the filter slightly hardens the photon spectra, especially for Al- and Be-target spectra which have large low-energy components.[41,42] The value of the pure photon %dd(10) for the filtered beam increases by up to 1% compared to its unfiltered value for an Al- or Be-target spectrum. However, this effect is smaller for the

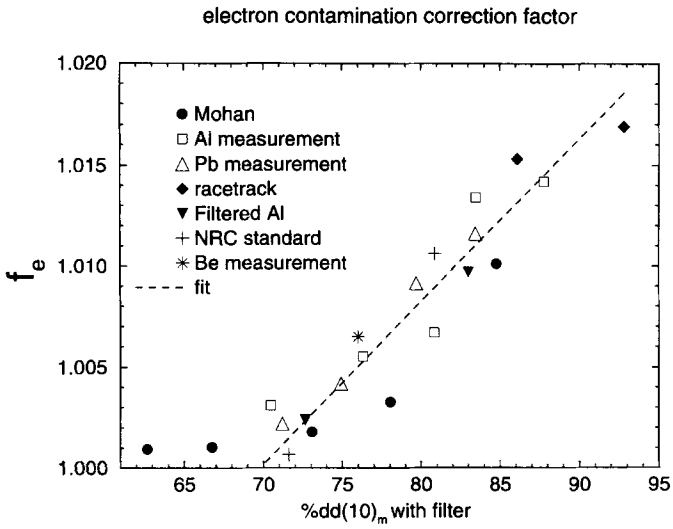

FIG. 5. The electron contamination correction factor, f_e, calculated for the spectra filtered by a 0.1-cm lead foil and 50 cm of air. For a filtered beam, the measured %dd(10)$_m$ value multiplied by f_e gives the %dd(10) value for the photon component of filtered beam. A linear relation as given by Eq. (3) is used to fit the data points. The statistical uncertainty on individual values of f_e is ±0.05%.

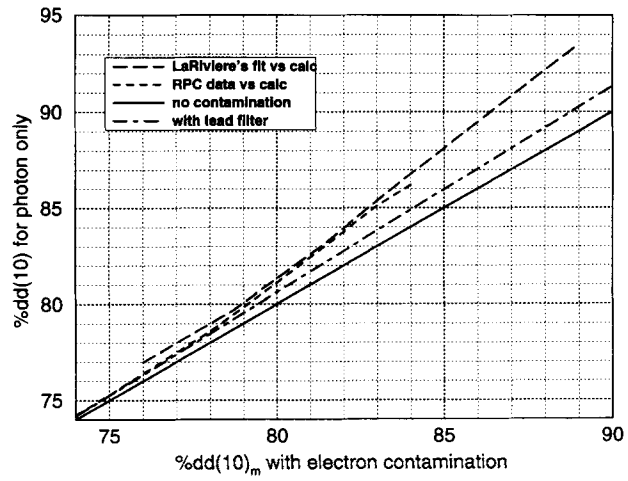

FIG. 6. Comparison of the %dd(10) for pure photon beams with the %dd(10)$_m$ which includes the effects of electron contamination for typical clinical photon spectra. The y-axis values are those calculated for pure photon beams,[6] while those of the x axis are the measured or calculated values including electron contamination at the maximum dose and dose at 10-cm depth. RPC data are the measured data extracted from the Radiological Physics Center's data base. The top line is extracted from LaRiviere's fit to his measured %dd(10) data. The curve for a lead filter is calculated by using the fitted f_e value in Fig. 5.

clinical spectra calculated by Mohan *et al.* which had high-Z targets, and for the Pb-target measured spectra. In these cases the value of the pure photon %dd(10) for the filtered beam is approximately 0.15% higher than that for the unfiltered value. For a precise determination of a clinical-linac beam quality index, this photon filtering effect should be taken into account.

B. Correction for electron contamination

For all the photon beams considered here the calculations show that the effect of the electron contamination generated from the filter and the air past the filter is too small to shift the depth of the dose maximum in a 100-cm^2 field. The effect of electron contamination can be completely removed from the %dd(10) value with the filter in place [hereafter %dd(10)$_m$, which includes the effects of electron contamination from the filter and air only] by multiplying it by the corresponding value of the electron-contamination correction factor, f_e, as defined above. This gives the %dd(10) value for just the photon component of the filtered beam. Figure 5 presents the values of f_e vs the %dd(10)$_m$ values calculated for the spectra filtered by a 0.1-cm lead foil, which include contributions from both incident photons and the secondary electrons generated in the filter and the air past the filter. For beams with %dd(10)$_m \geq 70\%$, the linear function

$$f_e = 0.9439 + 0.000\,804[\%\mathrm{dd}(10)_m] \quad (4)$$

was found to fit all 19 data points with an rms deviation of 0.0017 and a maximum deviation of 0.0034. The values of f_e calculated for lead here can be also used for other materials from Sn to Pb when filters have the same thickness of 1.13 g/cm^2. The error in this approach is within ±0.07% for the material range studied. It is found that the effect of electron contamination at 10-cm depth; i.e., the value of $D^e_{10}/D^{\mathrm{tot}}_{10}$ is very small (less than 0.02%) for beams with %dd(10)$\leq$80%, or with $Q<19$ MV [Eq. (1)]. Thus it is not necessary to correct for the effects of electron contamination at 10-cm depth except for very high-energy beams.

The statistical uncertainty on the individual values of f_e is very small (±0.05%) since the electron dose is only a few percent or less of the maximum photon dose. The variation of f_e for the same value of %dd(10)$_m$ is ±0.3% as seen from Fig. 5. However, the error introduced in the stopping-power ratio by this variation is negligible (0.05%), as seen from Fig. 1.

Although there is considerable fluctuation in the raw data, Kosunen and Rogers[6] extracted estimates of the effects of electron contamination on %dd(10)$_m$ from two sources, the Radiological Physics Center's data base and LaRiviere's analysis.[8] These estimates are shown in Fig. 6 as a comparison of %dd(10) with and without electron contamination. The values of the %dd(10) for photons only (y axis) are those calculated for pure photon beams, while those with electron contamination (x axis) are the measured or calculated values including the effects of electron contamination. The curve showing the effects with a lead filter in place is calculated using the fitted values of f_e, as given in Fig. 5 and taking the photon filtering effects for high-Z target beams into account. It is seen from Fig. 6 that the filter substantially reduces electron contamination (e.g., from 3% to 1% for the beam with %dd(10)$_m$=85%), provided that the filter removes all upstream electrons. More importantly, the fluctuations about the fitted line with the filter in place (0.17% rms deviation, see Fig. 5) are negligible whereas the fluctuations about the other fitted lines are substantial because of the variations in electron contamination from various accelerators (see Ref. 6). The effect of the remaining electron contamination can be simply eliminated by f_e. Figure 6 also

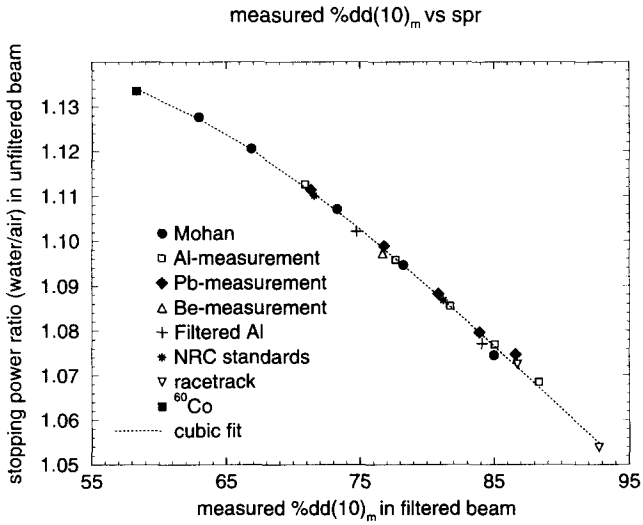

FIG. 7. The water-to-air stopping power ratio for unfiltered beam versus total (measured) percentage depth dose in a 100-cm^2 photon beam at an SSD of 100 cm. %dd(10)$_m$ calculated for the photon beam filtered by a 0.1-cm lead filter and 50 cm of air. A cubic function given by Eq. (5) is chosen to fit the data points. The stopping power ratio for the unfiltered beam can be directly determined from this plot when %dd(10)$_m$ is measured for a filtered photon beam.

shows that the filters are only needed for high-energy photon beams [say for beams with %dd(10)$_m \geq 73\%$, or with $Q \geq 10$ MV, Eq. (1)].

C. Stopping-power ratio vs %dd(10)$_m$

Figure 7 presents the water-to-air stopping-power ratios in *unfiltered* beams plotted against the values of %dd(10)$_m$ for all the filtered beams considered here. The values of stopping-power ratio are no longer linearly related to the values of the %dd(10)$_m$, as they were for the pure photon %dd(10) reported by Kosunen and Rogers[6] and seen in Fig. 1. This is because the effects of secondary electrons generated in the filter and the air past the filter are included in the measured %dd(10)$_m$ values in Fig. 7, as are the photon filtering effects (i.e., beam hardening effects). It is found that for the stopping power ratios of the unfiltered beams, a cubic function

$$\left(\frac{\bar{L}}{\rho}\right)_{\text{air}}^{\text{water}} = 0.9578 + (8.802E-3)[\%\text{dd}(10)_m] - (1.254E-4)[\%\text{dd}(10)_m]^2 + (4.509E-7)[\%\text{dd}(10)_m]^3 \quad (5)$$

fits all 23 data points with an rms deviation of 0.0009 and a maximum deviation of 0.0024.

Thus, in a clinic one has a choice of the following two methods to determine stopping-power ratio.

(i) Calculate the pure photon %dd(10) for the unfiltered beam by using the measured %dd(10)$_m$ for the lead filtered beam in two steps: (a) Eliminate the effect of electron contamination by multiplying %dd(10)$_m$ by the corresponding f_e value determined from Fig. 5 or from Eq. (3), and (b) account for the beam-hardening effect of the filter by subtracting 0.15% of the value obtained from the first step. The value of the stopping-power ratio for the unfiltered beam is determined using Fig. 1 or by Eq. (2).

(ii) Determine the stopping-power ratio for the unfiltered beam directly from Fig. 7 or from Eq. (5) using %dd(10)$_m$ measured with the lead filter in place.

The first method makes clear each physical step in the process. The second one completely by-passes the pure photon %dd(10), and simply uses %dd(10)$_m$ to obtain the water-to-air stopping-power ratio. The values of the stopping-power ratios determined using the two methods are consistent with each other within the statistical uncertainty although in the second case individual corrections for beam hardening were made.

The %dd(10) in a pure photon beam specifies stopping-power ratios within 0.2% for all thick-target bremsstrahlung beams as reported in Ref. 6. The measured %dd(10)$_m$ for the filtered beam, which includes the effects of the electron contamination and the beam hardening by the filter, also specifies stopping-power ratio for the unfiltered beam within 0.2% for all filtered beams considered here as seen from Fig. 7. A discussion of how accurately %dd(10)$_m$ needs to be measured is given in Ref. 6.

The water-to-air stopping-power ratios are calculated at a depth of 10 cm. It has been found that the variation in stopping-power ratios between 5- and 10-cm depth is less than 0.1% except those for the beams with $Q \geq 25$ MV for which 5-cm depth is in the buildup region. The behavior of stopping-power ratios at 5-cm depth vs %dd(10)$_m$ is generally the same as that at 10-cm depth.

The above procedures assume the unfiltered beam is to be calibrated. However the filtered beam usually reduces unwanted dose to the patient and could be used for treatment. To calibrate the filtered beam one simply uses f_e [Eq. (4)] to correct the value of %dd(10)$_m$ for electron contamination from the filter and air and then applies Eq. (2) to determine the water to air stopping-power ratio. In this case there is no need to correct for the beam hardening effects of the filter.

IV. CONCLUSIONS

The percentage depth dose at 10 cm in a 100-cm^2 photon beam at an SSD of 100 cm, %dd(10), is a better beam-quality specifier for radiotherapy beams than the commonly used values of TPR_{10}^{20} or nominal accelerating potential. The problem of electron contamination when measuring %dd(10) is solved by using a 0.1-cm lead filter, which reduces the surface dose from contaminant electrons from the accelerator by more than 95% for radiotherapy beams with energies from ^{60}Co to 50 MV. The filter performs best when it is placed immediately downstream from the accelerator head. The electron-contamination correction factor, f_e, is introduced to convert measured %dd(10)$_m$, which includes electron contamination in a filtered beam, into the %dd(10) for the photon component of the filtered beam. It is a linear function of the %dd(10)$_m$ for all the beams with %dd(10)$_m$ greater than 70%. The correction for the photon filtering effect converts the pure photon %dd(10) for a filtered beam into that for the unfiltered beam. It is found that the values of water-to-air stopping power ratio for the unfiltered beams are

related to the values of the $\%dd(10)_m$ by a cubic function for all the filtered beams. Clinically, one can directly use the $\%dd(10)_m$ measured with a filter in place to obtain the corresponding water-to-air stopping power ratio in the unfiltered beam with an uncertainty of 0.2%.

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