Correcting for electron contamination at dose maximum in photon beams

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(Received 17 September 1998; accepted for publication 27 January 1999)

Data are presented to allow the photon beam quality specifier being used in the new AAPM TG-51 protocol, $\%dd(10)_x$, to be extracted from depth-dose data measured with a 1 mm lead foil either 50 cm or 30 cm from the phantom surface. $\%dd(10)_x$ is the photon component of the percentage depth dose at 10 cm depth for a 10×10 cm^2 field on the surface of a phantom at an SSD of 100 cm. The purpose of the foil is to remove the unknown electron contamination from the accelerator head. Monte Carlo calculations are done: (a) to show these electrons are reduced to a negligible level; (b) to calculate the amount of electron contamination from the lead foil at the depth of dose maximum; and (c) to calculate the effect of beam hardening on $\%dd(10)$. The analysis extends the earlier work of Li and Rogers [Med. Phys. **21**, 791–798 (1994)] which only provided data for the foil at 50 cm. An error in the earlier Monte Carlo simulations is reported and a more convenient method of analyzing and using the data is presented. It is shown that 20% variations in the foil thickness have a negligible effect on the calculated corrections. [S0094-2405(99)01104-9]

Key words: photon beam dosimetry, beam quality specification, electron contamination, Monte Carlo

I. INTRODUCTION

In the AAPM's TG-51 protocol for photon and electron beam dosimetry[1–3] the beam-quality specifier for photon beams is $\%dd(10)_x$, the photon component of the percentage depth-dose at 10 cm depth for a field size of 10×10 cm^2 on the surface of a phantom at an SSD of 100 cm. The advantage of this specifier over the previously used TPR_{10}^{20} is that variations in ion chamber response per unit absorbed dose are much less using this specifier.[4,5] The disadvantage is that one must account for the electron contamination which can affect the dose at the depth of dose maximum and hence affect $\%dd(10)_x$. The problem is that this electron contamination is machine dependent. There is a general estimate of this contamination which is thought to be good to within 2% of dose maximum.[4,6] This 2% uncertainty in $\%dd(10)_x$ leads to a 0.4% uncertainty in the dose assigned using the new protocol because the value of the quality conversion factor, k_Q, varies by about 0.2% per change in $\%dd(10)_x$ of 1% (e.g., 76%–75%). Some might consider this marginally acceptable, except that the global fit is based on data available in 1991/1992. At that time there were few multi-leaf collimators (MLCs) being used and when an MLC is added to a machine it may substantially decrease the distance between the accelerator and the phantom and thereby increase the electron contamination considerably. Hence the global fit may not be relevant to these newer machines.

To take into account the effects of electron contamination to better than 2%, Li and Rogers[7] proposed a method whereby a 1 mm lead foil is placed just below the accelerator head and one measures $\%dd(10)_{\mathrm{Pb}}$, the percentage depth-dose at 10 cm with the foil in place. The earlier paper demonstrated that the foil effectively removed all electron contamination from the accelerator head, which is variable from machine to machine, and that the calculated amount of electron contamination from the lead foil could be accurately predicted from the measured $\%dd(10)_{\mathrm{Pb}}$. However, the data presented for extracting $\%dd(10)_x$ from $\%dd(10)_{\mathrm{Pb}}$ were for the lead foil placed roughly 50 cm from the phantom surface. This distance was achievable for most accelerators in 1992/93, but as pointed out above, this is no longer the case, especially for machines with tertiary MLCs. Thus the original purpose of the work reported here was to extend the earlier work to the case of a 1 mm lead foil placed 30 cm above the phantom surface when beam quality is being determined for the open beam. In the process of doing this, a mistake was discovered in the previous calculations for the foil at 50 cm. The electron contamination from the lead foil was underestimated in the original paper.[7]

The present paper reports corrected values for extracting $\%dd(10)_x$ for the open beam from the value of $\%dd(10)_{\mathrm{Pb}}$ measured with a 1 mm lead foil placed at either 30 cm or 50 cm from the phantom surface.

II. CALCULATIONS AND QUANTITIES OF INTEREST

The BEAM code[6] is used for most of the Monte Carlo calculations done for this work. BEAM is a general purpose EGS4 user-code[8] which is designed to simulate accelerator beams efficiently. However, in this application the actual accelerator beams are not modeled but rather a standard set of photon beam spectra are used as described previously.[4,7] Also, simple electron spectra are used as inputs to some calculations. The advantage of using BEAM is that it can calculate central-axis depth-dose curves efficiently because of the

sophisticated range rejection techniques applied. BEAM also has a built-in facility for separately keeping track of the doses from photons and electrons incident on the phantom after passing through the foil. It is this aspect of the previous calculations which were in error due to a logic fault in the algorithm to assign the dose components.

In the calculations, electrons are tracked down to 700 keV total energy. In the depth-dose curves, dose is scored in circular regions of radius 1.5 cm and depth bins of 2 mm are used near the dose maximum to ensure the depth of dose maximum is determined accurately since the electron contamination changes rapidly with depth. Larger depth bins (up to 2 cm) are used around 10 cm depth to improve the statistics. At dose maximum, statistical uncertainty is kept well below 0.5% in order to specify the depth of dose maximum accurately. This requires up to 100 million photon histories.

Several different quantities are calculated.

In one set of runs, the relative dose is calculated for electron beams passing either through just 50 cm of air or 50 cm of air with a 1 mm lead sheet 30 or 50 cm from the phantom surface. The purpose of this calculation is to establish how effectively the 1 mm lead foil removes the electron contamination from the accelerator head. The dose is scored as a function of depth in the phantom for initial beams of electrons which are used to represent worst case situations (an estimate of the electron spectrum in a 50 MV beam as described earlier[7] and crude estimates of the electron spectrum based on NRC calculations of Varian 18 and 24 MV accelerators).

The purpose of another set of calculations is to determine the electron contamination generated by different photon beams passing through a 1 mm lead foil. The various photon spectra start from a point source, 100 cm from the water phantom, incident on a 10×10 cm^2 field at the phantom surface. The lead foil is included in the simulation at either 30 or 50 cm from the phantom surface. Air is present out to 50 cm from the phantom in all cases. In these calculations the total dose and the dose from the electron contaminants entering the phantom are scored. These data give $\%dd(10)_{\mathrm{Pb}}$ and the electron contamination at the depth of dose maximum, $d_{\max}$, and at 10 cm (if any). The previous paper[7] defined a quantity, f_e, that converts $\%dd(10)_{\mathrm{Pb}}$, which includes electron contamination generated in the filter and the air past the filter, into $\%dd(10)_{x,\mathrm{Pb}}$, which is for just the photon component of the filtered beam, i.e.,:

$$f_e=\frac{\%dd(10)_{x,\mathrm{Pb}}}{\%dd(10)_{\mathrm{Pb}}}. \tag{1}$$

The value of f_e was calculated as:

$$f_e^{\mathrm{calc}}=\frac{1-(D_{10}^e/D_{10}^{\mathrm{tot}})}{1-(D_{\max}^e/D_{\max}^{\mathrm{tot}})}, \tag{2}$$

where D_{10}^e and $D_{\max}^e$ are the doses due to contaminant electrons at 10 cm depth and at the maximum depth for the *total* dose, $d_{\max}$, while D_{10}^{tot} and $D_{\max}^{\mathrm{tot}}$ are the total doses at 10 cm depth and $d_{\max}$, respectively. As long as the electron contamination does not affect the depth of dose maximum in the filtered beam, then $f_e=f_e^{\mathrm{calc}}$. If the electron contamination at 10 cm is negligible, $f_e^{\mathrm{calc}}=1/(1-D_{\max}^e/D_{\max}^{\mathrm{tot}})\approx1+D_{\max}^e/D_{\max}^{\mathrm{tot}}$. Note that the statistical precision of this calculation is high because it is not directly dependent on the precision of the calculated total dose, only the precision of the electron contamination dose as a fraction of the total dose. The previous work[7] reported a linear relationship between $\%dd(10)_{\mathrm{Pb}}$ and f_e for values of $\%dd(10)_{\mathrm{Pb}}>70\%$. This was used as the first step in a two step process whereby f_e corrected $\%dd(10)_{\mathrm{Pb}}$ to $\%dd(10)_{x,\mathrm{Pb}}$. The second step was to note that for clinical spectra, on average, the filter caused a 0.15% increase in $\%dd(10)_x$ and this was used to determine $\%dd(10)_x$ from $\%dd(10)_{x,\mathrm{Pb}}$.

In the present analysis three new quantities, f_e', Δ_{shift} and Δ_{filter} are defined as:

$$f_e'=\frac{\%dd(10)_x}{\%dd(10)_{\mathrm{Pb}}}, \tag{3}$$

$$\Delta_{\mathrm{shift}}=\frac{D_{x,\mathrm{Pb}}(d_{\max}^{\mathrm{Pb}})}{D_{x,\mathrm{Pb}}(d_{\max}^{x,\mathrm{Pb}})}, \tag{4}$$

and

$$\Delta_{\mathrm{filter}}=\frac{\%dd(10)_{x,\mathrm{Pb}}}{\%dd(10)_x}, \tag{5}$$

where $D_{x,\mathrm{Pb}}(d)$ is the dose at depth d in the photon component of the filtered beam. The quantity Δ_{filter} is a correction to f_e^{calc}. It accounts for the shift in $d_{\max}$ caused by the electron contamination, especially when the lead foil is 30 cm from the phantom surface. At the 50 cm position, the previous paper reported that the effect of the shift was negligible[7] and hence $f_e=f_e^{\mathrm{calc}}$. However, if $d_{\max}$ does shift between the total depth-dose curve and the depth-dose curve for just the photons, then:

$$f_e=f_e^{\mathrm{calc}}\Delta_{\mathrm{shift}}. \tag{6}$$

The present results confirm that Δ_{shift} is negligible for the lead foil at 50 cm (>0.998) but that it can be as much as 1% less than unity for the foil at 30 cm. The uncertainty in Δ_{shift} is hard to assess because of the correlated nature of the quantities involved. It is estimated to be 0.2%.

The factor Δ_{filter} quantifies the effects of photon beam hardening by the lead filter which generally increases $\%dd(10)_x$ slightly. The quantity f_e' converts the percentage depth dose measured with the lead filter in place, to the value of $\%dd(10)_x$ in the **open** beam. Operationally f_e' is determined as:

$$f_e'=\frac{\Delta_{\mathrm{shift}}}{\Delta_{\mathrm{filter}}}f_e^{\mathrm{calc}}, \tag{7}$$

where f_e^{calc} is determined as above [Eq. (2)], Δ_{shift} is deduced from the calculated photon component of the depth-dose curve with the filter in place, and Δ_{filter} is determined as follows in separate, high precision calculations using the code DDSPR[4,9] which calculates $\%dd(10)_x$ for an arbitrary

spectrum. For a given accelerator spectrum, the filtered spectrum at the phantom surface after passing through a 1 mm lead foil at 30 or 50 cm from the phantom is determined in a separate EGS4 calculation.[7] The DDSPR code is then used to determine $\%dd(10)_x$ for both the filtered and unfiltered spectra and Δ_{filter} determined from Eq. (5).

The advantage of using this procedure [Eq. (7)] to determine f'_e is that it has a high statistical precision ($\pm 0.2\%$), whereas the values determined using Eq. (3) and the Monte Carlo calculated values of $\%dd(10)_x$ and $\%dd(10)_{\text{Pb}}$ have a total uncertainty of well over 0.5%.

The code DDSPR uses a simple $1/r^2$ correction to determine the values of $\%dd(10)_x$ at a finite SSD for values calculated for parallel beams. This is an approximation.[5,10] Nonetheless, the differences in $\%dd(10)_x$ between the filtered and unfiltered spectra are expected to be calculated accurately by DDSPR.

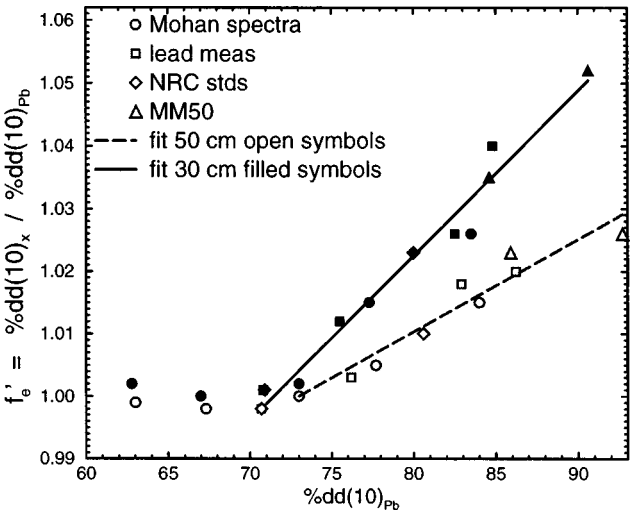

FIG. 1. Individual and fitted values of f'_e vs $\%dd(10)_{\text{Pb}}$ for a 1 mm thick lead foil at either 30 cm (filled symbols, solid line) or 50 cm (open symbols, dashed line). f'_e is the ratio of $\%dd(10)_x$ to $\%dd(10)_{\text{Pb}}$.

III. RESULTS

A. Effects of lead filter on accelerator electrons

With the corrected calculations, the first issue is whether a 1 mm lead foil adequately reduces the dose caused by the electron contamination from the accelerator head. In Fig. 2 of Li and Rogers,[7] the surface dose from an electron spectrum representative of a 50 MV beam from a racetrack microtron was reduced to 1% of the open-beam surface dose by a 1 mm lead foil at 50 cm from a water phantom. The same calculations with the BEAM code only predicts a reduction of the dose to 2.9%. For a 24 MeV monoenergetic electron beam the reduction goes from the previous value of 4% to 10%. These are extreme cases. For more realistic worst cases, namely for electron spectra typical of an 18 or 24 MV machine, the lead foil reduces the dose on the surface to 1% of the open-beam dose value. If the 1 mm lead foil is only 30 cm from the phantom surface, the angular scattering is not as effective at removing the electrons from the beam and the surface dose is only reduced to 3% of the open-beam electron dose for the electrons in the 18 and 24 MV beams and to 7% for the MM50 50 MV electron spectrum.

Furthermore, the situation is somewhat worse if one considers the dose reduction at the depth corresponding to the depth of dose maximum. For example, for the 24 MV electron spectrum the dose at $d_{\max}$ is only reduced to 4% or 1.5% of the open-beam dose for the foil at 30 and 50 cm, respectively.

With all of that said, these calculations still show that the lead foil reduces the electron combination from the accelerators to negligible levels. Consider a worst case scenario in an accelerator photon beam where the electron contamination at $d_{\max}$ is 4% of the maximum dose. If the 1 mm lead foil at 30 cm reduces this to 4% of its open field value, that corresponds to an electron contamination from the accelerator generated electrons of 0.16% of dose maximum and correspondingly less in other cases.

B. Values of f'_e

The effect of the logic error in the earlier calculations[7] is not as dramatic when considering the electron contamination generated by photon beams passing through a 1 mm lead foil. Nonetheless the values of f_e increase, typically by 0.5%, and in the worst case by 1% for those beams with high enough energy to generate 2% electron contamination at $d_{\max}$.

Figure 1 presents a plot of the new quantity f'_e vs $\%dd(10)_{\text{Pb}}$ for a variety of photon spectra. The values of f'_e display less fluctuation than a similar plot of f_e vs $\%dd(10)_{\text{Pb}}$ (not shown). Several things are clear. First, f'_e, the correction needed to go from $\%dd(10)_{\text{Pb}}$ to $\%dd(10)_x$, is given by a simple straight line fit to the data in each case: i.e., the amount of electron contamination from the lead foil can be easily predicted and is independent of the details about the spectrum other than $\%dd(10)_{\text{Pb}}$. The second observation is that, as expected, for the foil 30 cm from the phantom surface, the contamination is significantly higher.

The values of f'_e shown by the straight line least square fits in Fig. 1 are given by:

$$f'_e = 0.8116 + 0.00264\%dd(10)_{\text{Pb}} \quad [\text{foil at } 30 \text{ cm}, \%dd(10)_{\text{Pb}} \geqslant 71\%] \tag{8}$$

or

$$f'_e = 0.8905 + 0.00150\%dd(10)_{\text{Pb}} \quad [\text{foil at } 50 \text{ cm}, \%dd(10)_{\text{Pb}} \geqslant 73\%]. \tag{9}$$

For values of $\%dd(10)_{\text{Pb}}$ less than the respective thresholds, $f'_e = 1.0$.

If we use these fits rather than the individual data, the worse case is that f'_e is wrong by 0.5% which means the measured value of $\%dd(10)_x$ is wrong by 0.5%. This leads to a 0.1% error in the dose assigned using the k_Q formalism of the TG-51 protocol.[3]

The figure shows that for $\%dd(10)_{Pb}$ values up to 73%, f'_e values are 1.00, i.e., $\%dd(10)_x = \%dd(10)_{Pb}$. Since photon beams of 10 MV tend to have $\%dd(10)_x$ values of 70%–73%, this means $\%dd(10)_x = \%dd(10)_{Pb}$ for beams with energies of 10 MV or less. The issue arises, should the lead foil measurements be done for 10 MV beams or can one use $\%dd(10)_x = \%dd(10)$, where $\%dd(10)$ is measured in the open beam? In the 10 MV beams the electron contamination from the lead is between 0.4% and 1.0%, but this is offset by the photon filtering effects to a large extent. However, if one uses $\%dd(10)_x = \%dd(10)$ and assumes that electron contamination from the accelerators is roughly the same as from the lead foils (i.e., up to 1%), then the error in the dose assigned is up to 0.2%. The error is more if the electron contamination from the accelerators is greater, as is likely with tertiary MLCs since they are closer to the phantom. Since the measurement with the lead foil is no more difficult than the measurement without the lead foil in place, it is probably worth using the lead foil for 10 MV machines. For energies below this, the electron contamination at d_{max} in a 10×10 cm^2 field has a negligible effect on the dose assignment and one can take $\%dd(10)_x = \%dd(10)$.

C. Filter thickness

The above calculations are all done for lead foils which are exactly 1 mm thick. However, real foils will vary in thickness. The issue is: how carefully must this thickness be controlled? In the original paper[7] it was shown that the amount of electron contamination from the accelerator head that gets through the lead foil is a slowly varying function of the foil thickness and that foils of about 1 mm thickness get rid of all such electrons.

Calculations have been done for the 24 MV Mohan spectrum with the lead foil at 30 cm from the phantom and varying the foil thickness between 0.8 and 1.2 mm. As the foil thickness varies by 20% from the nominal 1 mm thickness, the change in the electron contamination and hence in the value of f'_e is less than 0.2%. Thus as long as the foil is within 20% of its nominal thickness, there is a negligible variation in the formulae presented above.

IV. SUMMARY AND CONCLUSIONS

Data are presented for converting $\%dd(10)_{Pb}$ into $\%dd(10)_x$, i.e., for converting the percentage depth-dose at 10 cm depth in a 10×10 cm^2 field measured with a 1 mm lead foil in place to the corresponding percentage depth-dose for the photon component only of the open beam. In doing the calculations for the foil at 30 cm to extend the earlier data for a foil at 50 cm, it is found that the previous calculations had a logic error in the coding (although the overall effect of this error on the predicted value of $\%dd(10)_x$ is less than 0.6% for beams of 25 MV or less). In redoing the calculations, a new parameter, f'_e is defined which takes into account the effects of the filtering by the lead foil in each individual beam and this reduces the scatter in the final results about the fitted line. It is also necessary to account for effects on f'_e of the shift in dose maximum caused by electron contamination from the lead foil, although the effect is only significant when the foil is 30 cm from the phantom. This parameter is also more easily used since it directly relates the measured quantity, $\%dd(10)_{Pb}$, to the quantity of interest, $\%dd(10)_x$. It is shown that f'_e is accurately given in terms of the measured quantity $\%dd(10)_{Pb}$ and hence the overall equations for $\%dd(10)_x$ are:

$$\%dd(10)_x = [0.8116 + 0.00264\%dd(10)_{Pb}]\%dd(10)_{Pb} \quad [\text{foil at } 30 \text{ cm}, \%dd(10)_{Pb} \geq 71\%] \qquad (10)$$

and

$$\%dd(10)_x = [0.8905 + 0.00150\%dd(10)_{Pb}]\%dd(10)_{Pb} \quad [\text{foil at } 50 \text{ cm}, \%dd(10)_{Pb} \geq 73\%] \qquad (11)$$

and for $\%dd(10)_{Pb}$ below 71% or 73%, respectively (i.e., beams below 10 MV), one takes $\%dd(10)_x = \%dd(10)_{Pb}$ or alternatively $\%dd(10)_x = \%dd(10)$, i.e., no measurements are needed with the lead foils since the electron contamination at these energies has a negligible effect on $\%dd(10)$.

Calculations with foils 20% thicker and thinner than the nominal 1 mm foil thickness show that the results are insensitive to the actual thickness of the foil within these tolerances.

Although this paper provides data for using the lead foil as close as 30 cm to the phantom, it must be remembered that the previous paper showed[7] that the amount of electron contamination varies with distance from the phantom and that this variation is more pronounced at 30 cm than at 50 cm. Thus the tolerances on positioning the foils are tighter at 30 cm than at 50 cm. In general the size of the correction at 30 cm is greater than at 50 cm and hence the overall uncertainty is larger. Also, the ''leakage'' of electrons through the foil from the accelerator head is substantially higher at 30 cm. Taken together these considerations suggest that the foil should be placed 50 cm from the phantom surface if at all possible, in order to minimize uncertainties.

ACKNOWLEDGMENTS

I would like to thank my colleagues Blake Walters for assisting with some of the data analysis and Daryoush Sheikh-Bagheri for his BEAM code input files for the Varian 18 MV beam which were used to get an estimate of the electron spectra in 18 and 24 MV machines. Thanks also to Dr. Carl Ross for useful comments on the manuscript. This work was supported, in part, by NIH/NCI Grant No. R01-CA66852.

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