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0. Abstract

Two dosimetry protocols based on absorbed dose to water have recently been implemented: TG-51 and TRS-398. These protocols use different beam quality indices: %dd(10)_x and TPR_{20,10}. The effect of electron contamination in measurements of %dd(10)_x has been proposed as a disadvantage of the TG-51. For actual measurements of %dd(10)_x on five clinical beams (Primus 6–18 MV, SL-75/5 6 MV, SL-18 6–15 MV) a purging magnet was employed to remove the electron contamination. Also, %dd(10)_x was measured in the different ways described in TG-51 for high-energy beams: with a lead foil at 50 cm from the phantom surface, at 30 cm, and for open beam. Moreover, TPR_{20,10} was determined. Considering both protocols, S_{w,air} and k_Q were calculated in order to compare the results with the experimental data. Significant differences (0.3% for k_Q) were only found for the two high-energy beams, but when the electron contamination is underestimated by TG-51, the difference in k_Q is lower. Differences in the other cases and variations were less than 0.1%.

1. Introduction

In recent years, two new dosimetry protocols based on absorbed-dose-to-water have been implemented: TG-51 of the AAPM [1]; and An International Code of Practice for Dosimetry based on Standards of Absorbed Dose to Water (TRS-398) of the IAEA [2]. Both propose procedures in which dose to water in the user beam are derived from an absorbed dose to water calibration factor, N_{P,w,Q_0} in a reference beam quality Q_0. Previous protocols (TG-21 [3], TRS-381 [4], TRS-277 [5]) were based on air kerma standard. A beam quality dependence correction factor, denoted as k_{Q,Q_0}, is used to fit to the user beam quality, Q. Direct measurements of k_{Q,Q_0} at the same quality as the user beam are not feasible in most standard laboratories, and therefore theoretical values [6][7][8] are commonly used. Each protocol uses a different beam-quality index: TPR_{20,10} in TRS-398 and %dd(10)_x of TG-51. The effect of electron contamination in measurements of %dd(10)_x has been proposed as a disadvantage of TG-51. On the other hand, the benefits of using %dd(10)_x, Rogers [8], Li and Rogers [9], Kosunen and Rogers [10] have remarked the linearity of the relation between stopping power ratio and %dd(10)_x even for non clinical beams, such as photon beams of some standards laboratories.

The main argument against the use of %dd(10)_x expressed by Andreo [11][12] is that electron contamination is calculated for general machines, considering some clinical spectra, but not for the actual machine where measurements are being performed. Electron contamination is machine-dependent, but has should not affect the beam-quality correction factor. The use of clinical beams for direct k_{Q,Q_0} measurements in primary standards laboratories, has been proposed by this author and TPR_{20,10} as the beam quality index.
A purging magnet has been performed to remove the electron contamination. This electron contamination can be determined for each beam, and measured %dd(10)_x can be compared with %dd(10)_x calculated from %dd(10)_Pb or %dd(10) in the different ways described in TG-51. On the other hand, TPR_{30,10} has been determined as another beam quality index. Considering both protocols and related literature, S_{w,air} and k_Q have been calculated in order to compare results with experimental data.

2. Materials and methods

The measurements were performed in five photon beams in a Siemens Primus and two Elekta linacs (SL-18 and a SL75/5). The five clinical beams are: 6 and 18 MV by Primus, 6 and 15 MV by SL-18, and 6MV by SL-75/5 installed in the Radiotherapy Department of the Hospital do Meixoeiro.

2.1 Purging magnet design

TG-51 calculates %dd(10)_x from depth dose profiles of a filtered beam by a lead foil. This foil must be placed at 50 ± 5 cm from the phantom surface. For measurements of %dd(10)_x in five clinical beams a purging magnet has been performed. A U-shaped iron structure was constructed in order to confine the magnetic field. Each magnet of Nd-Fe-B was placed on one arm of the U-shaped structure. The magnetic field measured in the centre of the beam is 0.2 T and a gap of 10 cm (maximum field size available: 13 – 12 cm depending on the machine) is obtained. Magnetic field in the centre of the magnet is similar to previous measurements with purging magnets [13][14][15][16].

2.2 Beam quality specification

Central axis depth dose profiles were measured with a Wellhöfer IC-10 cylindrical ionization chamber in a computerized Scanditronix-Wellhöfer WP700 water tank. Field size at beam axis was set to 10 x 10 cm², and SSD was fixed at 100 cm. For low energy measurements, only two depth dose profiles were obtained for each beam: with magnet and in open beam.

For the Primus 18 MV beam eleven depth dose profiles were measured: in open beam, with the magnet, with a 1 mm thick lead foil at 51, 50, 49, 45.2 and 30 cm from the phantom surface, and with magnet and the lead foil at 51, 50, 49, 45.2. The last set of measurements with the magnet and the lead foil was performed to determine any additional beam-hardening effect. Also, variation with lead foil positioning was measured.

For the SL-18 15 MV beam five depth dose profiles were measured: in open beam, with magnet, with lead foil at 46.2 and 29.2 cm from the phantom surface, and with magnet and lead foil at 46.2 cm.

%dd(10)_x was determined directly with depth-dose curves measured using the magnet and estimated with TG-51 formulae for open beam and measurements with lead foil. In the case of open beam and low energies, TG-51 estimates %dd(10)_x = %dd(10), but for higher energies ( 75% < %dd(10) < 89% ) uses the following expression:

%dd(10)_x = 1.267 × %dd(10) – 20        \hspace{1cm} (1)

which reduces [10] the uncertainty in S_{w,air} to 0.2% (0.4% with no correction).

When the lead foil is positioned at 50 ± 5 cm from the phantom surface and %dd(10)_Pb ≥ 73%, the correcting expression is:

%dd(10)_x = (0.8905 + 0.00150 × %dd(10)_Pb) × %dd(10)_Pb        \hspace{1cm} (2)

Finally, if lead foil is placed at 30 ± 1 cm from the phantom surface and %dd(10)_Pb ≥ 71%:
\[
\%dd(10)_x = (0.8116 + 0.00264 \times \%dd(10)_{Pb}) \times \%dd(10)_{Pb}
\]  
(3)

These last two corrections, have a maximum uncertainty [17] of 0.5%. Thus if a rectangular probability density is considered, the type B uncertainty due to these fits can be set to 0.3%.

According to Rogers and Yang [18], the relationship between \%dd(10)_x and \(S_{w,air}\) is:

\[
S_{w,air} = 1.275 - 0.00231 \times \%dd(10)_x.
\]  
(4)

The associated standard deviation to this fit is 0.0011.

TPR\textsubscript{20,10} was measured in the five beams with the Wellhöfer IC-10 chamber using a Scanditronix-Wellhöfer WP700 3D scanning system, but varying the water level instead of moving the chamber. Measurements were made as described in Andreo & Brahme [19], while TPR\textsubscript{20,10} in SL-18 was performed with SSD = 100 cm. For calculation of stopping power ratio, the next cubic fit was used [20]:

\[
S_{w,air} = 1.3614 - 1.2963 \times \text{TPR}_{20,10} + 2.5302 \times (\text{TPR}_{20,10})^2 - 1.6896 \times (\text{TPR}_{20,10})^3
\]  
(5)

This expression fits the data better than 0.15%, and type B standard uncertainty of 0.09% was used.

Both new protocols are based on absorbed-dose-to-water, and \(S_{w,air}\) was used for calculations of \(k_Q\), until direct measurements are available. \(S_{w,air}\) and \(p_{wall}\) are the main source of uncertainty in \(k_Q\) calculations. Anyway, tabulated values of \(k_Q\) were compared from both protocols for each beam.

3. Results

3.1 Electron contamination

Depth dose measurements were normalized at 10 cm depth. As a result of measurements with and without magnet, depth ionization variation doubt to electron contamination has been measured for a field size of 10 x 10 cm\textsuperscript{2} at SSD = SAD = 100 cm.

For the three low energy beams, electron contamination from treatment head was determined and is shown in figure 1. Estimation of electron contamination in the maximum can be obtained from equations 1 – 3. Comparisons of measured electron contamination at maximum depth and estimated values with TG-51 formulae are presented in table I. All these values are referred to dose at 10 cm depth.
Table I Comparison of measured electron contamination in the maximum and estimated values with TG-51.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Energy</th>
<th>Modifier</th>
<th>Position of maximum (cm)</th>
<th>Electron contamination</th>
<th>Electron contamination by TG-51 estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primus</td>
<td>6 MV</td>
<td>None - open beam</td>
<td>1.6</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>SL75</td>
<td>6 MV</td>
<td>None - open beam</td>
<td>1.4</td>
<td>0.8</td>
<td>0</td>
</tr>
<tr>
<td>SL18</td>
<td>6 MV</td>
<td>None - open beam</td>
<td>1.5</td>
<td>0.8</td>
<td>0</td>
</tr>
<tr>
<td>SL18</td>
<td>15 MV</td>
<td>None - open beam</td>
<td>2.8</td>
<td>2.3</td>
<td>0.6</td>
</tr>
<tr>
<td>SL18</td>
<td>15 MV</td>
<td>Lead at 46.2 cm</td>
<td>2.9</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>SL18</td>
<td>15 MV</td>
<td>Lead at 29.2 cm</td>
<td>3</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Primus</td>
<td>18 MV</td>
<td>None - open beam</td>
<td>3.1</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Primus</td>
<td>18 MV</td>
<td>Lead at 50 cm</td>
<td>3.2</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Primus</td>
<td>18 MV</td>
<td>Lead at 30 cm</td>
<td>3</td>
<td>1.9</td>
<td>2.1</td>
</tr>
</tbody>
</table>

According to TG-51, it is recommended that the lead foil be placed at 50 ± 5 cm. Variations in electron contamination due to positioning lead foil 45 cm to 55 cm from the water surface has been studied for the Primus 18 MV beam. The lead foil was placed at 45.2 cm, 49 cm, 50 cm and 51 cm. Variations are lesser than experimental uncertainty and can be seen in figure 2. Figure 3 indicates that electron contamination was higher for the lead foil place placed at 30 cm than for open geometry of the latter beam.
Beam hardening effect is also considered, but comparison of measurements with magnet and with or without lead foil; show that no beam hardening effect is measured beyond experimental uncertainty.

3.2 Quality indices and stopping power ratios ($S_{w,air}$)

In table II the quality indices measured for the three low energy beams can be seen. Uncertainty has also been estimated. In the low energy measurements, only experimental uncertainty is considered.
Table II Quality indices measured for several low energy beams.

<table>
<thead>
<tr>
<th>Machine / Method</th>
<th>Energy</th>
<th>Method</th>
<th>Quality index</th>
<th>$u_{S_{w,air}}$</th>
<th>$u_{d_{AB}}$</th>
<th>$u_A$</th>
<th>$u_B$</th>
<th>kQ NE2571</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primus 6MV</strong>, TRS-398 IC10</td>
<td>6MV</td>
<td>TG-51 open beam</td>
<td>TPR$_{20,10}$</td>
<td>0.6738</td>
<td>0.0013</td>
<td>1.1198</td>
<td>0.0010</td>
<td>0.993</td>
</tr>
<tr>
<td><strong>Primus 6MV</strong>, TG-51 open beam</td>
<td>6MV</td>
<td>TG-51 + purging magnet</td>
<td>%dd(10)</td>
<td>66.98</td>
<td>0.20</td>
<td>1.1203</td>
<td>0.0012</td>
<td>0.994</td>
</tr>
<tr>
<td><strong>SL18 6MV</strong>, TRS-398</td>
<td>6MV</td>
<td>TG-51 open beam</td>
<td>TPR$_{20,10}^2$</td>
<td>0.6822</td>
<td>0.0011</td>
<td>1.1195</td>
<td>0.0012</td>
<td>0.993</td>
</tr>
<tr>
<td><strong>SL18 6MV</strong>, TG-51 open beam</td>
<td>6MV</td>
<td>TG-51 + purging magnet</td>
<td>%dd(10)</td>
<td>67.29</td>
<td>0.25</td>
<td>1.1195</td>
<td>0.0012</td>
<td>0.993</td>
</tr>
<tr>
<td><strong>SL75 6MV</strong>, TRS-398</td>
<td>6MV</td>
<td>TG-51 open beam</td>
<td>TPR$_{20,10}^2$</td>
<td>0.6767</td>
<td>0.0012</td>
<td>1.1193</td>
<td>0.0010</td>
<td>0.993</td>
</tr>
<tr>
<td><strong>SL75 6MV</strong>, TG-51 + purging magnet</td>
<td>6MV</td>
<td>%dd(10)</td>
<td>67.61</td>
<td>0.12</td>
<td>1.1199</td>
<td>0.0011</td>
<td>0.993</td>
<td></td>
</tr>
</tbody>
</table>

The results of beam quality index for high energy beams are shown in table III. In this table, uncertainty for %dd(10) was considered experimental uncertainties and type B uncertainties where available.

Table III Quality indices measured for several low energy beams

<table>
<thead>
<tr>
<th>Machine / Energy, Method</th>
<th>Energy</th>
<th>Method</th>
<th>Quality index</th>
<th>$u_{S_{w,air}}$</th>
<th>$u_{d_{AB}}$</th>
<th>$u_A$</th>
<th>$u_B$</th>
<th>kQ NE2571</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primus 18MV</strong>, TRS-398 IC10</td>
<td>18MV</td>
<td>TG-51 open beam</td>
<td>TPR$_{20,10}$</td>
<td>0.7704</td>
<td>0.0013</td>
<td>1.0919</td>
<td>0.0011</td>
<td>0.978</td>
</tr>
<tr>
<td><strong>Primus 18MV</strong>, TG-51 open beam</td>
<td>18MV</td>
<td>TG-51 lead at 45.2 cm</td>
<td>%dd(10)$_h$</td>
<td>78.79</td>
<td>0.14</td>
<td>1.0930</td>
<td>0.0022</td>
<td>0.976</td>
</tr>
<tr>
<td><strong>Primus 18MV</strong>, TG-51 lead at 45.2 cm + magnet</td>
<td>18MV</td>
<td>%dd(10)$_h$</td>
<td>78.73</td>
<td>0.36</td>
<td>1.0931</td>
<td>0.0014</td>
<td>0.976</td>
<td></td>
</tr>
<tr>
<td><strong>Primus 18MV</strong>, TG-51 lead at 49 cm</td>
<td>18MV</td>
<td>%dd(10)$_h$</td>
<td>78.62</td>
<td>0.21</td>
<td>1.0934</td>
<td>0.0012</td>
<td>0.976</td>
<td></td>
</tr>
<tr>
<td><strong>Primus 18MV</strong>, TG-51 lead at 49 cm + magnet</td>
<td>18MV</td>
<td>%dd(10)$_h$</td>
<td>78.38</td>
<td>0.32</td>
<td>1.0939</td>
<td>0.0013</td>
<td>0.976</td>
<td></td>
</tr>
<tr>
<td><strong>Primus 18MV</strong>, TG-51 lead at 50 cm</td>
<td>18MV</td>
<td>%dd(10)$_h$</td>
<td>79.03</td>
<td>0.22</td>
<td>1.0924</td>
<td>0.0012</td>
<td>0.975</td>
<td></td>
</tr>
<tr>
<td><strong>Primus 18MV</strong>, TG-51 lead at 50 cm + magnet</td>
<td>18MV</td>
<td>%dd(10)$_h$</td>
<td>78.91</td>
<td>0.32</td>
<td>1.0927</td>
<td>0.0013</td>
<td>0.975</td>
<td></td>
</tr>
<tr>
<td><strong>Primus 18MV</strong>, TG-51 lead at 51 cm</td>
<td>18MV</td>
<td>%dd(10)$_h$</td>
<td>78.83</td>
<td>0.19</td>
<td>1.0929</td>
<td>0.0012</td>
<td>0.975</td>
<td></td>
</tr>
<tr>
<td><strong>Primus 18MV</strong>, TG-51 lead at 51 cm + magnet</td>
<td>18MV</td>
<td>%dd(10)$_h$</td>
<td>78.66</td>
<td>0.33</td>
<td>1.0933</td>
<td>0.0013</td>
<td>0.976</td>
<td></td>
</tr>
<tr>
<td><strong>Primus 18MV</strong>, TG-51 lead at 30 cm</td>
<td>18MV</td>
<td>%dd(10)$_h$</td>
<td>78.38</td>
<td>0.20</td>
<td>1.0940</td>
<td>0.0012</td>
<td>0.976</td>
<td></td>
</tr>
<tr>
<td><strong>Primus 18MV</strong>, TG-51 + purging magnet</td>
<td>18MV</td>
<td>%dd(10)$_h$</td>
<td>79.13</td>
<td>0.29</td>
<td>1.0922</td>
<td>0.0013</td>
<td>0.975</td>
<td></td>
</tr>
<tr>
<td><strong>SL18 15MV</strong>, TRS-398</td>
<td>15MV</td>
<td>TG-51 open beam</td>
<td>TPR$_{20,10}^2$</td>
<td>0.7650</td>
<td>0.0012</td>
<td>1.0940</td>
<td>0.0011</td>
<td>0.980</td>
</tr>
<tr>
<td><strong>SL18 15MV</strong>, TG-51 lead at 46.2 cm</td>
<td>15MV</td>
<td>%dd(10)$_h$</td>
<td>76.64</td>
<td>0.10</td>
<td>1.0980</td>
<td>0.0022</td>
<td>0.979</td>
<td></td>
</tr>
<tr>
<td><strong>SL18 15MV</strong>, TG-51 lead at 46.2 cm + magnet</td>
<td>15MV</td>
<td>%dd(10)$_h$</td>
<td>77.38</td>
<td>0.45</td>
<td>1.0963</td>
<td>0.0015</td>
<td>0.979</td>
<td></td>
</tr>
<tr>
<td><strong>SL18 15MV</strong>, TG-51 lead at 29.2 cm</td>
<td>15MV</td>
<td>%dd(10)$_h$</td>
<td>77.52</td>
<td>0.09</td>
<td>1.0959</td>
<td>0.0011</td>
<td>0.980</td>
<td></td>
</tr>
<tr>
<td><strong>SL18 15MV</strong>, TG-51 + purging magnet</td>
<td>15MV</td>
<td>%dd(10)$_h$</td>
<td>77.48</td>
<td>0.31</td>
<td>1.0960</td>
<td>0.0013</td>
<td>0.978</td>
<td></td>
</tr>
</tbody>
</table>

The uncertainty of $S_{w,air}$ was divided into two independent uncertainties: those associated with experimental uncertainty ($u_A$) of quality indices, and uncertainties ($u_B$) caused by stopping-power-ratio fitting as a function of beam-quality index and %dd(10)$_x$ calculations from %dd(10)$_{pb}$.
In SL-18 15 MV significant differences were found, especially for open beam measurements. In open beam, TG-51 underestimates electron contamination, so this difference could be explained by this result.

4. Discussion

Theoretical comparison made by Huq et al [21] shows that the quotient of beam quality factors, $k_Q$, from both protocols is between $1.000 \pm 0.001$, except for $75\% < \%dd(10)_x < 85\%$ or $0.70 < TPR_{20,10} < 0.77$, where lower values were found, although the $k_Q$ values agree within 0.2% for almost the entire range of photon beam qualities used in hospitals. The greatest difference in calculated $k_Q$ from our measurements was found for SL-18 15 MV beam: 0.3% (for purging magnet measurements), but for stopping power ratios, the biggest difference was 0.4%, for open beam (for purging magnet measurements the difference is only 0.15%). Electron contamination is underestimated in TG-51 for this open beam but this fact tends to compensate the expected difference. Theoretical maximum difference was found for $TPR_{20,10} = 0.75$ (measured beam: $TPR_{20,10} = 0.765$), similar to beam quality index of measured 15 MV beam. Expected difference for this beam is .3%, which is the difference value obtained for measurements with magnet, but measurements in open beam, with underestimated electron contaminations, differs only 0.1%. Landoni et al [22] found similar results comparing TRS-398 and TG-51. In a Clinac 2100CD 15 MV beam ($\%dd(10)_x = 77.7$; $TPR_{20,10} = 0.756$) difference for both protocols was 0.4% for a PTW 30002 chamber.

Several measurements of experimental $k_Q$ values have been measured in the last few years [23][24][25]. These values are comparable to data from table II for both protocols for the three 6 MV beams.

$TPR_{20,10}$ for SL-18 15 MV beam is 0.765, so the expected value of $k_Q$ from table II referred to above reference is $0.974 \pm 0.010$. The closest value to experimental data is $k_Q$ obtained with $\%dd(10)_x$ measured with purging magnet, although its calculated value of $S_{w,air}$ is closer to calculated values from $TPR_{20,10}$ than other $\%dd(10)_x$ measured.

For Primus 18 MV beam, the best agreement between $k_Q$ calculated from our measurements and experimental values is again obtained for measurements of $\%dd(10)_x$ measured with the purging magnet. Experimental values are 0.973-0.972 and are similar to calculated values: 0.975 – 0.978 (Tables II and III).

The greatest difference between calculated $\%dd(10)_x$ from $\%dd(10)_Pb$ and direct measured $\%dd(10)_x$ is for SL-18 15 MV beam and it was 1% (see table III). This difference is higher than expected for fit uncertainty [17]: maximum of 0.5%. Although this difference is so high, differences in $S_{w,air}$ were kept below 0.06%, lower than uncertainty associated to $S_{w,air}$ linear fit. Measurements in open beam are quite different. For the same beam, the difference $S_{w,air}$ ($TPR_{20,10}$) and $S_{w,air}$ ($\%dd(10)_x$) from open beam measurement was +0.2%. Anyway, with regard to this energy, the theoretical difference [21] is -0.3%, differences in $k_Q$ cannot be appreciated and, surprisingly, differences are lower in this case. Also, it must be noted that electron contamination is not always reduced by placing a lead foil. Figure 3 shows that electron contamination is higher when the lead foil is positioned at 30 cm from the water surface, but differences between $\%dd(10)_x$, from $\%dd(10)_Pb$ and directly measured $\%dd(10)_x$ are of the same order as uncertainty.

5. Conclusions

A purging magnet was designed based on a permanent magnet of Nd-Fe-B and removed all electrons produced in the treatment head. Electron contamination from the treatment head has been measured for a squared field of $10 \times 10 \text{ cm}^2$ and SSD = 100 cm. It can be seen that electron contamination is very machine dependent, and not only dependent on beam energy. More detailed results can be seen in the reference [26].
Pure photon beam depth dose profiles were used to measure $%dd(10)$ directly, using the purging magnet, and these values were compared with TG-51 calculated values from measurements in filtered and open beams. Associated-to-fit uncertainties to calculate beam quality index in TG-51 were reviewed and compared with TRS-398 uncertainties. Similar uncertainties were found in both protocols. For comparing protocols, two parameters were used: $S_{w,air}$ and $k_Q$. Calculated $k_Q$ was compared with recent experimental $k_Q$. For measurements at low energies, differences are lower than uncertainty and the deviation in experimental data offered by several authors is much higher. For high energy, closest agreement with experimental data was found using $%dd(10)$, although electron contamination was not always correctly estimated (lead at 30 cm for 18 MV beam, and open beam for 15 MV). Nonetheless, the greatest discrepancy observed between both protocols is 0.3%[21].

6. References


