WATER EQUIVALENCY OF SOME PLASTIC MATERIALS USED IN ELECTRON DOSIMETRY: A MONTE CARLO INVESTIGATION*

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(Received September 26, 2006)

Abstract. The aim of this paper is to calculate, using Monte Carlo simulations, the depth-scaling factors $c_{pl}$ and fluence-scaling factors $h_{pl}$ of some commercially available water substitute solid phantoms in order to evaluate their water equivalency. Two sets of calculations have been done: for electron pencil beams and for $10 \times 10$ cm$^2$ parallel beams normally incident on water and solid phantoms. We have used only mono-energetic beams of 6, 9, 12, 15 and 18 MeV.

Key words: dosimetry, electron beams, plastic phantoms, IAEA TRS-398.

1. INTRODUCTION

Water is recommended by major dosimetry protocols [1–4] to be used as the standard phantom material for the dosimetry of high-energy electrons. However, it is not always possible or practical to perform dosimetry measurements in a water phantom. Plastic phantoms may be used under certain circumstances for electron beam dosimetry for beam qualities $R_{50} < 4g/cm^2$ (beam energy $E_0$ below 10 MeV).

Presently, many different plastic materials are used for dosimetry purposes in radiotherapy and radiophysics departments: white and clear polystyrene, PMMA, Solid water WT1, Solid water RMI-457, Virtual water, Plastic water, etc. Several articles comparing the equivalency of various plastics (as phantom material) to water for electron beam dosimetry have been published [5–9]. Ideally, the phantom material should be water equivalent; that is, it should have the same absorption and scatter properties as water for selected range of photon or electron energies used clinically. In fact, no plastic material is perfectly water-equivalent and dose distributions in solid phantoms do not match perfectly those in the water phantoms.

Although the use of plastic phantoms for reference electron dosimetry is strongly discouraged by the TRS-398 IAEA international dosimetry protocol, due to the large discrepancies in determination of the absorbed dose, they could be used when no waterproof chamber is available or when accurate positioning in water is not possible. When a plastic is used, the dose-distribution in the solid phantom must be converted to appropriate dose-distribution in water by means of a depth-scaling factor, \( c_{pl} \). In addition, the dosimeter reading \( M_{Q,pl} \) at any depth in plastic should be scaled to the equivalent reading in water, \( M_Q \), using a fluence-scaling factor, \( h_{pl} \). The aim of this paper is to calculate, using Monte Carlo simulations, depth-scaling factors \( c_{pl} \) and fluence-scaling factors \( h_{pl} \) of some commercially available water substitute solid phantoms for mono-energetic pencil beam and 10 × 10 cm\(^2\) parallel electron beams. Our calculations are actually limited only to five electron beams within a range of energies from 6 MeV to 18 MeV. The results are compared with the TRS-398 recommended values and the water-equivalency of plastic materials for the investigated beams is discussed.

2. MATERIALS AND METHODS

2.1. THEORETICAL BACKGROUND

Depth dose distribution in solid phantom can be converted to appropriate depth dose distribution in water by means of depth-scaling. For a measurement made at a depth \( z_{pl} \) (g·cm\(^{-2}\)) in a solid phantom, appropriate depth in water \( z_w \) (g·cm\(^{-2}\)) is given by [2]

\[
 z_w = z_{pl} c_{pl},
\]

where \( c_{pl} \) is a depth-scaling factor.

To convert a reading of ionization chamber in the solid phantom to an appropriate reading in water, the fluence-scaling factor has been proposed in the TRS-389 [2]. The reading of ionization chamber \( M_{Q,pl} \) in the solid phantom must be scaled to the appropriate reading \( M_Q \) in water using the following equation

\[
 M_Q = M_{Q,pl} h_{pl},
\]

in which \( h_{pl} \) is the fluence-scaling factor. When \( M_{Q,pl} \) is a reading of the ionization chamber at \( z_{ref,pl} \) in the solid phantom and \( M_Q \) is a reading at \( z_{ref} \) in water, \( h_{pl} \) is defined as

\[
 h_{pl} = \frac{M_Q}{M_{Q,pl}}.
\]
2.2. MONTE CARLO SIMULATIONS

2.2.1. Depth-scaling factor

The elemental composition, mass fraction, nominal density and mean atomic number for plastic materials investigated in this work are summarized in Table 1. Depth-scaling factor $c_{pl}$ for each medium can be calculated as the ratio of the average depth of electron penetration in water and the solid phantom [8]:

$$c_{pl} = \frac{z_{av}^w \rho_w}{z_{av}^p \rho_p},$$  \hspace{1cm} (4)$$

where $z_{av}^w$ and $z_{av}^p$ is an average penetration depth (cm) in water and solid phantom, and $\rho_w$ and $\rho_p$ is density (g⋅cm$^{-3}$) of water and solid phantom material, respectively.

<table>
<thead>
<tr>
<th>Z</th>
<th>A</th>
<th>Water</th>
<th>Polystyrene</th>
<th>PMMA</th>
<th>WT1</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1</td>
<td>1.008</td>
<td>0.112</td>
<td>0.077</td>
<td>0.081</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>12.011</td>
<td>0.923</td>
<td>0.600</td>
<td>0.672</td>
</tr>
<tr>
<td>N</td>
<td>7</td>
<td>14.007</td>
<td>0.320</td>
<td>0.199</td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>8</td>
<td>15.999</td>
<td>0.888</td>
<td>1.19</td>
<td>1.02</td>
</tr>
</tbody>
</table>

We used the EGSnrc Monte Carlo code [10] to calculate $z_{av}$. Mono-energetic electron pencil beams and 10 $\times$ 10 cm$^2$ electron parallel beams of energies 6, 9, 12, 15 and 18 MeV were assumed to impinge normally on the finite slab of water and the other materials (see Table 1). The transport of primary electrons was followed down to the cut-off energy at 10 keV, penetration depths $z_i$ of each history were sampled and $z_{av}$ was calculated.

2.2.2. Fluence-scaling factor

In the case of identical irradiation condition, when the absorbed dose to water is $D_w$ and the absorbed dose to solid phantom is $D_{pl}$, the fluence-scaling factor can be calculated [8] as

$$R_{pl} = \frac{M_Q}{M_{Q, pl}} = \frac{D_w}{D_{pl}} s_{pl, w},$$  \hspace{1cm} (5)$$

where $s_{pl, w}$ is the plastic material-to-water stopping power ratio.
Fig. 1 – Absorbed depth dose in water phantom: (a) different energies; (b) different media; (c) different beam sizes.
In this work, absorbed dose distributions were calculated using DOSXYZnrc [11] and stopping power ratios (SPRs) with SPRZnrc [12] Monte Carlo code. The fluence-scaling factors were determined using formula (5).

3. RESULTS AND DISCUSSION

3.1. DEPTH DOSE DISTRIBUTIONS

Depth dose distributions were calculated for monoenergetic 6 to 18 MeV electron pencil beams and $10 \times 10 \text{ cm}^2$ electron parallel beams normally incident on water and plastic materials phantoms investigated in this paper. Comparison after electron energy, media and beam size are shown in Fig. 1a, b and c, respectively. Each distribution is normalized to the maximum dose value. The necessity of depth scaling is illustrated by Fig. 1b, while the significant differences between

![Graph](image)  
*Fig. 2 – Polystyrene to water stopping-power ratios: (a) different beam energies; (b) different beam sizes.*
dose distributions obtained with pencil and $10 \times 10$ cm$^2$ parallel beams are shown in Fig. 1c.

3.2. STOPPING-POWER RATIOS

An example of plastic-to-water stopping power ratios (SPRs) calculated as a function of depth for each electron energy is given in Fig. 2a. In Fig. 2b a comparison is shown between polystyrene-to-water SPRs obtained with pencil and $10 \times 10$ cm$^2$ parallel beams, similar distributions being obtained for each material and energy investigated. Passing from pencil beams to $10 \times 10$ cm$^2$ parallel beams, minor differences between SPRs values are introduced. As a consequence, the mean values of plastic-to-air SPRs are practically independent of the electron beam size (see Table 2).
### Table 2

<table>
<thead>
<tr>
<th>Material</th>
<th>Polystyrene</th>
<th>PMMA</th>
<th>WTI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stopping power ratio, $s_{pl,w}$</td>
<td>0.976</td>
<td>0.969</td>
<td>0.977</td>
</tr>
</tbody>
</table>

### 3.3. DEPTH-SCALING FACTOR

The TRS-398 only recommends depth-scaling factors for $10 \times 10 \text{ cm}^2$ beams (reference beams). Due to the size beam dependence on depth dose distributions, these factors could have different values when smaller non-reference beams are used. In Figs. 3a and 3b depth-scaling factors $c_{pl}$ are shown as a function of the electron energy calculated for pencil beams and for $10 \times 10 \text{ cm}^2$ parallel beams, respectively. The $c_{pl}$ values for pencil beams are generally lower (see also Table 3) than reference beam values (up to 10%). However, only the $c_{pl}$s calculated for

![Graph](image1)

**Fig. 4** – Ratio of absorbed dose at reference depth in water to depth in solid phantom $D_w/D_{pl}$: (a) pencil beam; (b) $10 \times 10 \text{ cm}^2$ parallel beam.
larger beams can be compared with those recommended by TRS-398, and only for beam qualities $R_{50} < 4 \text{ g/cm}^2$ ($E_0 < 10 \text{ MeV}$). Excepting the polystyrene case, our results are very close to those previously calculated by Saitoh et al. [8] and in good agreement with $c_{pl}$ of TRS-398.

Table 3
Mean depth-scaling factors, $c_{pl}$, for solid water substitutes materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Polystyrene</th>
<th>PMMA</th>
<th>WT1</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work (pencil beam)</td>
<td>0.883</td>
<td>0.807</td>
<td>0.954</td>
</tr>
<tr>
<td>This work (10 × 10 cm$^2$ beam)</td>
<td>0.930 (+0.9%)</td>
<td>0.945 (+0.4%)</td>
<td>0.952 (+0.3%)</td>
</tr>
<tr>
<td>Saitoh et al. [8]</td>
<td>0.927 (+0.5%)</td>
<td>0.944 (+0.3%)</td>
<td>0.952 (+0.3%)</td>
</tr>
<tr>
<td>TRS-398</td>
<td>0.922</td>
<td>0.941</td>
<td>0.949</td>
</tr>
</tbody>
</table>

Fig. 5 – Fluence scaling factors $h_{pl}$ as a function of electron energy:
(a) pencil beam; (b) 10 × 10 cm$^2$ parallel beam.
3.4. FLUENCE-SCALING FACTOR

Fig. 4 shows the ratio of absorbed dose at reference depth in water to that in solid phantom. The uncertainty of absorbed dose ratio may be estimated as 0.6–0.8% for both pencil and reference beams. The fluence-scaling factors were derived from these absorbed dose ratios $D_{\text{water}}/D_{\text{pl}}$ and the above-mentioned stopping power ratios $s_{\text{pl}, w}$ using equation (5). Fig. 5 shows the fluence-scaling factor $h_{\text{pl}}$ as a function of electron energy. The mean value of $h_{\text{pl}}$ (calculated only for 6 and 9 MeV) for several materials are tabulated in Table 4. In the case of pencil beams, the $h_{\text{pl}}$ values are generally lower than the $10 \times 10 \text{ cm}^2$ values. The $h_{\text{pl}}$ for solid water WT1 gave good agreement with that of TRS-389, however, the other materials give a significant difference.

Finally, we evaluated the percentage depth dose distributions in solid phantoms with and without scaling for pencil and $10 \times 10 \text{ cm}^2$ parallel beams.

![Diagram](image)

Fig. 6 – Comparison of depth dose distributions obtained in pure water and polystyrene (without and with $c_{\text{pl}}$ correction) in the case of: (a) pencil beam; (b) $10 \times 10 \text{ cm}^2$ parallel beam.
Table 4

Mean fluence-scaling factors, $h_{pl}$, for solid water substitutes materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Polystyrene</th>
<th>PMMA</th>
<th>WT1</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work (pencil beam)</td>
<td>1.018</td>
<td>1.013</td>
<td>1.011</td>
</tr>
<tr>
<td>This work (10 × 10 cm² beam)</td>
<td>1.037 (+1.1%)</td>
<td>1.018 (+0.9%)</td>
<td>1.017 (+0.6%)</td>
</tr>
<tr>
<td>Saitoh et al. [8]</td>
<td>1.035 (+0.9%)</td>
<td>1.024 (+1.5%)</td>
<td>1.019 (+0.8%)</td>
</tr>
<tr>
<td>TRS-398</td>
<td>1.026</td>
<td>1.009</td>
<td>1.011</td>
</tr>
</tbody>
</table>

Generally good agreement between dose distributions in water and those obtained by IAEA scaling method using $c_{pl}$ factors was obtained for both pencil and 10 × 10 cm² electron beams, although in the latter case we observed some minor differences near the surface and at the end of the electron range (see, for instance, Fig. 6b).

4. CONCLUSIONS

The water equivalence of polystyrene, PMMA and solid water WT1, used only in certain circumstances for electron beam dosimetry, was evaluated using Monte Carlo simulations. Depth-scaling factors $c_{pl}$ and fluence-scaling factors $h_{pl}$ were determined in the case of pencil and 10 × 10 cm² electron beams normally incident on water and plastic phantoms. Only mono-energetic beam with 6, 9, 12, 15 and 18 MeV were used.

We found that in the case of pencil beams, both scaling factors have lower values (for $c_{pl}$ up to 10%) than those calculated for 10 × 10 cm² electron parallel beams. In the case of 10 × 10 cm² parallel beam our results are close to those previously calculated by Saitoh et al. [8] (excepting the polystyrene case) and in good agreement with the TRS-398 recommended values. As a result, it is obvious that the depth in the solid phantom can be converted to appropriate depth in water by means of depth-scaling using $c_{pl}$ factors.

REFERENCES


