Monte Carlo evaluation of water equivalency of some plastic materials for realistic electron IORT beams

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Abstract. The water equivalency of some commercially available water substitute materials for high energy electron beams dosimetry (PMMA, polystyrene and solid water WT1) has been investigated in this work for electron beams generated by the IORT linear accelerator NOVAC 7. The beams were simulated by the BEAMnrc/EGSnrc Monte Carlo code, while the dose distributions in water and plastic phantoms were calculated using DOSXYZnrc. The stopping power ratios were evaluated using SPRRZnrc user code. The results obtained for the depth- and fluence-scaling factors have been compared with the values recommended by the TRS-398 IAEA code of practice for absorbed dose determination in external beam radiotherapy. Due to the significant differences observed (sometimes more than 1%) and to the dependence of the scaling factors on the beam quality we can conclude that every time when plastic phantoms are used in electron IORT dosimetry, a theoretical or experimental investigation of the water equivalency of the water substitute materials must be done.

1. Introduction

IAEA TRS-398 [1] and other international dosimetry protocols recommend the use of water as standard phantom material for the dosimetry of high-energy electrons. For electron energies $E_0 < 10$ MeV, and only in special circumstances (when reference dosimetry measurements in a water phantom is difficult to perform), water-equivalent plastic materials may be used. In these circumstances, the dose-distribution in the solid phantom must be converted into appropriate dose-distribution in water by means of a depth-scaling factor, $c_{pl}$. Moreover, 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, $h_{pl}$.

In the case of conventional radiotherapy with electron beams, the use of $c_{pl}$ and $h_{pl}$ values given by international dosimetry protocols guarantees an acceptable level of accuracy. However, these protocols should be used with care in the case of electron beams generated by linear accelerators for Intra-Operative Radiation Therapy (IORT) because these accelerators have different dosimetric characteristics. The mobile accelerators are equipped with long cylindrical applicators. Due to their length, these applicators have a major contribution to the energy degradation, as well as to the spatial and angular distributions of the electrons at the phantom/patient surface [2]. Important parameters (as stopping power ratios and perturbation factors) used for absorbed dose determinations, depend on the electron beam characteristics. The correction factors and physical parameters recommended in the international dosimetry protocols [1, 3] are experimentally determined or calculated for conventional electron beams. Applying those data to beams such as those used for IORT could be, in principle, not appropriate if the characteristics of IORT and conventional beams are too much dissimilar from each other. Taking into account that, in the calibration procedures of electron beams, the accuracy of the dosimetric measurements must be as good as possible, such errors must be avoid.
In the present work is investigated the water equivalency of some plastic materials for realistic IORT beams generated by NOVAC7® linear accelerator calculating the values of scaling factors by a Monte Carlo method. The modelling of the NOVAC7® IORT accelerator is described in our previous work [2]. In the present calculations, only 3 MeV and 9 MeV electron beams and applicators having the extreme sizes (diameters of 4 and 10 cm) are used. The electron beams were obtained using BEAMnrc Monte Carlo code and dose distributions were calculated with DOSXYZnrc. The scaling factors have been evaluated through a technique described in our earlier works in which mono-energetic beams in interaction with polystyrene, PMMA and solid water WT1 were employed [4, 5]. Agreements until ~1% with TRS-398 international code of practice were obtained. However, a theoretical investigation of the water equivalency of water substitutes materials has never been reported for realistic beams generated by an IORT accelerator. It is well-known that the IORT beams are far to be mono-energetic, in fact being more degraded than the electron beams obtained with conventional accelerators. It is interesting to know if the values recommended by the IAEA TRS-398 dosimetry protocol for the scaling factors can be applied to electron beams generated by an IORT accelerator such as NOVAC7®. The main goal of our work is to give an answer to this question.

2. Theoretical considerations

According to the IAEA TRS-398 code of practice [2], solid phantoms in slab form such as polystyrene, PMMA, and certain epoxy resin “solid water” (water substitute) phantom materials such as solid water, plastic water, virtual water, etc. (see table 1 from the reference [5]) may be used for low energy electron beam dosimetry (under 10 MeV) and are generally required for low energy X rays dosimetry. However, the dose determination must always be referred to the absorbed dose to water at the reference depth in a homogeneous water phantom, the scaling procedure described in the TRS-398 code of practice being mandatory.

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

\[
z_w = z_{pl}c_{pl}\quad (1)
\]

where \(c_{pl}\) is the depth-scaling factor which can be calculated [6] by:

\[
c_{pl} = \frac{z_{w}^{2} \rho_{w}}{z_{pl}^{2} \rho_{pl}} = \frac{R_{50}^{w}}{R_{50}^{pl}}\quad (2)
\]

In the above equation, \(z_{w}^{2}\) and \(z_{pl}^{2}\) are the average penetration depths (i.e. the half-value depths, \(R_{50}\)) in water and plastic phantom, respectively, and \(\rho_{w}\), \(\rho_{pl}\) are the material densities.

In the case of identical irradiation conditions, when the absorbed dose to water is \(D_w\) and the absorbed dose in the solid (plastic) phantom is \(D_{pl}\), the fluence-scaling factor can be calculated using the following formula:

\[
h_{pl} = \frac{M_Q}{M_{Q,pl}} = \frac{D_w}{D_{pl}} s_{pl,w}\quad (3)
\]

where, according to IAEA TRS-398 [2], \(M_Q\) and \(M_{Q,pl}\) are the dosimeter readings at the reference depth

\[
z_{ref} = 0.6R_{50} - 0.1\text{ g/cm}^2\quad (R_{50}\text{ in g/cm}^2)\quad (4)
\]

in water and in the plastic phantom, respectively; \(s_{pl,w}\) is the plastic material-to-water mass stopping power ratio.

The IAEA recommended values for the depth-scaling factors \(c_{pl}\), fluence-scaling factors \(h_{pl}\) and the nominal densities \(\rho_{pl}\) for certain commercially available water substitute plastic materials are given in the table 21 (chapter 7) of the IAEA TRS-398 code of practice [2].
When using a plastic phantom to determine the depth dose distribution, each measurement depth in plastic must be scaled using equation (1) to give the appropriate depth in water. The dosimeter reading at each depth must also be scaled using equation (3).

3. Modelling

The NOVAC7® system is a robotic mobile intra-operative electron beam unit. This accelerator produces pulsed electron beams with four different nominal energies: 3, 5, 7 and 9 MeV. The accelerator is equipped with a 3D movable arm that can be pointed on the operating field. The basic system includes four types of Perspex (PMMA) cylindrical applicators with inner diameters 4, 6, 8 and 10 cm, wall thickness 0.5 cm and lengths 69, 67, 67 and 87 cm, respectively. The source-to-surface distance (SSD) is 80 cm, except for the applicator with the diameter of 10 cm for which the SSD is 100 cm. There are no scattering foils or flattening filters inside the treatment head, as the spatial uniformity of the treatment field is obtained by the scattering processes of electrons on the applicator wall [7].

The geometry of the NOVAC7® IORT accelerator (i.e. all of the essential components in the treatment head) was built using EGSnrc/BEAMnrc [8 - 10]. The accelerator was modelled as a series of simple BEAMnrc component modules with cylindrical symmetry centred on the z-axis (see the figure 1 from our previous work [2]). The shape, dimension and material of these components were simulated according to the information provided by the manufacturer.

A number of four IORT beams have been simulated in this work corresponding to the combination of the lowest and highest nominal energies (3 MeV and 9 MeV) with the applicators having the extreme sizes (4 cm and 10 cm).

For each simulated beam, the complete information (energy, position, direction, charge, etc.) about any particle that crosses a given plane perpendicular to the beam axis (scoring plane) was stored in a data file (the phase-space file) further used as input file for the calculation of dose distributions in water and plastic phantoms. The correctness of the simulations was verified by comparing the dose distributions calculated in the water phantom with the experimental dose distribution in water, as described in the reference [2]. An agreement of about 2% was obtained.

Depth dose distributions on the central axis of the four investigated beams where calculated in 20 x 20 x 5 cm$^3$ water, PMMA, polystyrene and WT1 phantoms of Cartesian voxel geometry using EGHSnrc user-code DOSXYZnrc [11]. Dose scoring grid was set to 1 cm x 1 cm x 0.1 cm. A number of 4·10$^7$ source electrons were using, ensuring a statistical uncertainty less than 1%.

The phase-space files at the phantom surface obtained for the IORT clinical beams were also used as source inputs for the EGSnrc/SPRZnrc code [12] to calculate Spencer–Attix stopping power ratios of plastic-to-water, $s_{pl,w}$, as a function of depth in phantom. The $s_{pl,w}$ values were calculated along the central axis of the beam in cylindrical regions with a thickness of 0.1 cm and a radius of 1 cm. The statistical uncertainties were less than 0.1%.

In all simulations, have been used default values for EGSnrc particle’s transport parameters, PRESTA-I for boundary crossing algorithm and PRESTA-II as electron transport algorithm. The cross section data were created using PEGS4 [10] including Sternheimer density effect corrections from ICRU 37 [13]. The energy cut-offs for particle transport were set to ECUT = AE = 0,521 MeV (kinetic energy plus rest mass) and PCUT = AP = 0,010 MeV.

4. Results and discussion

Percentage depth dose distributions in the water phantom for the IORT beams investigated in this work are shown in figure 1a. Each distribution is normalized to the maximum dose value. As we can see, in the case of the beams having 9 MeV nominal energy, the applicator size has practically no influence on dose distributions.

The necessity of depth scaling is illustrated by figure 1b. The significant deviation of the dose distribution curves in PMMA is due to the higher density of this material (1.19 g/cm$^3$) in comparison to water (1 g/cm$^3$), polystyrene (1.06 g/cm$^3$) and WT1 (1.02 g/cm$^3$). Nevertheless, the depth-scaling
factors calculated using equation (2) does not differ so much because the depths \( z_w \) and \( z_{pl} \) are expressed in g/cm\(^2\).

![Figure 1](image1.png)

**Figure 1.** Percentage dose distributions: (a) in the water phantom for the IORT beams investigated in this work (d = the applicator diameter, E = the nominal energy); (b) in different materials (d = 10 cm, E = 9 MeV).

The values of scaling factors calculated by the Monte Carlo method are given in table 2 and compared with the values recommended by the IAEA TRS-398 code of practice. The statistical uncertainties are less than ±0.3% (1\( \sigma \)) for the small applicator and less than ±0.4% (1\( \sigma \)) for the large field size applicator. However, a final estimation of the uncertainties should also refer to the experimental dose distributions. Taking into account the ±2% agreement [2] between calculated and experimental depth dose distributions in the water phantom, previously mentioned, the range of...
uncertainty should be unacceptable. Fortunately, in the regions of half-value ($R_{50}$) and reference ($z_{ref}$) depths, the 1σ uncertainties do not exceed ±0.9%. Assuming the same uncertainty for the other water substitute materials, the overall 1σ uncertainties for the scaling factors are ±0.95% (d = 4 cm applicator) and ±1% (d = 10 cm applicator). Comparing with TRS-398 values, generally higher values have been obtained (up to ~1%, with some exceptions – the bold values in table 2).

### Table 1. Spencer–Attix stopping power ratios plastic-to-water, $s_{plw}$ (for beams with 9 MeV nominal energy).

|        | PMMA | Polystyrene | WT1 |
|--------|------|-------------|-----|
| $s_{plw}$ | 0.968 | 0.975       | 0.977 |

An interesting case is that of the most degraded beam, i.e. the 3 MeV beam generated using the smallest applicator (d = 4 cm). In this case, in which the scattered component is larger than the direct component, the depth scaling factors are much smaller, negative deviations from the TRS-398 values (up to -5.7%) being obtained. For this beam, the same problem also arises in the case of the fluence-scaling factors, but deviations are positives this time and not so high (up to 2.4%). It is obvious and understandable that for such low energy beams, used only in the Intra-Operative Radiation Therapy, the TRS-398 values cannot be applied in practice without introducing unacceptable errors. For the rest of the beams, with some exceptions, we generally found an agreement in the limit of about ±1%, fact that suggest the applicability of the TRS-398 values.

### Table 2. Scaling factors for water substitute materials investigated in this work. In the first (left) column the values in parentheses are those recommended by the IAEA TRS-398 code of practice. Deviations from these values are given below the Monte Carlo calculated values. The bold values are deviations significantly exceeding the overall uncertainties of 0.95% and 1%.

| d = 4 cm E = 3 MeV | d = 4 cm E = 9 MeV | d = 10 cm E = 3 MeV | d = 10 cm E = 9 MeV | Mean values (*) |
|-------------------|-------------------|-------------------|-------------------|----------------|
| Depth-scaling factors, $c_{pl}$ |
| PMMA              | 0.925             | 0.938             | 0.944             | 0.948           | 0.943           |
| (0.941)            | (-1.7%)           | (-0.3%)           | (+0.3%)           | (+0.7%)         | (+0.2%)         |
| Polystyrene        | 0.871             | 0.931             | 0.932             | 0.937           | 0.933           |
| (0.922)            | (-5.5%)           | (+1.0%)           | (+1.1%)           | (+1.6%)         | (+1.2%)         |
| WT1                | 0.895             | 0.954             | 0.951             | 0.957           | 0.954           |
| (0.949)            | (-5.7%)           | (+0.5%)           | (+0.2%)           | (+0.8%)         | (+0.5%)         |
| Fluence-scaling factors, $h_{pl}$ |
| PMMA              | 1.024             | 1.006             | 1.024             | 1.015           | 1.015           |
| (1.009)            | (+1.5%)           | (-0.3%)           | (+1.5%)           | (+0.6%)         | (+0.6%)         |
| Polystyrene        | 1.051             | 1.036             | 1.051             | 1.036           | 1.041           |
| (1.026)            | (+2.4%)           | (+1.0%)           | (+2.4%)           | (+1.0%)         | (+1.5%)         |
| WT1                | 1.029             | 1.022             | 1.029             | 1.020           | 1.027           |
| (1.011)            | (+1.8%)           | (+1.1%)           | (+1.8%)           | (+0.9%)         | (+1.6%)         |

(*) Excepting the most degraded beam (d = 4 cm, E = 3 MeV).

Taking into account that only the extreme cases have been chosen for the Monte Carlo investigation (the smallest and biggest applicator, the lowest and highest nominal energies) we can conclude that for other combinations applicator-nominal energy the scaling factors should have values situated somewhat between those obtained in this work (see the last column from table 2). However, without experimental validation (which is the purpose of a future work) we cannot suggest the application of these results in the real measurements.
5. Conclusions

Water equivalence of PMMA, polystyrene and solid water (WT1) for realistic beams generated by the NOVAC 7 IORT accelerator was investigated by the Monte Carlo method. Only four IORT beams have been used: a combination of the lower and higher nominal energies (3 and 9 MeV) with the thinnest and the thickest applicator (4 and 10 cm). The depth- and fluence-scaling factors were calculated and compared with the values recommended by the IAEA TRS-398 dosimetry protocol. The results obtained for the four beams investigated in this work show a clear dependence on the beam quality, especially in the case of depth-scaling factors. However, in most cases, deviations ~ 1% from the TRS-398 values have been obtained, excepting the beam with a nominal energy of 3 MeV obtained with an applicator of 4 cm in diameter for which the deviations go until -5.7%. Taking into account these results, we conclude that for an accurate dosimetry a preliminary investigation of the water equivalence of the water substitute materials should be performed. Otherwise, the use of these materials - not recommended by the international dosimetry protocols but permitted in some special circumstances - could introduce larger and unknown errors, at risk being especially the low energy beams.

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