Properties of Water Substitute Solid Phantoms for Electron Dosimetry

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ABSTRACT

To reduce the uncertainty in the calibration of radiation beams, absorbed dose to water for high energy electrons is recommended as the standards and reference absorbed dose by AAPM Report no.51 and IAEA Technical Reports no.398. In these recommendations, water is defined as the reference medium, however, the water substitute solid phantoms are discouraged. Nevertheless, when accurate chamber positioning in water is not possible, or when no waterproof chamber is available, their use is permitted at beam qualities $R_{50} < 4$ g/cm^2 ($E_0 < 10$ MeV). For the electron dosimetry using solid phantom, a depth-scaling factor is used for the conversion of depth in solid phantoms to depth in water, and a fluence-scaling factor is used for the conversion of ionization chamber reading in plastic phantom to reading in water. In this work, the properties, especially depth-scaling factors c_{pl} and fluence-scaling factors h_{pl} of several commercially available water substitute solid phantoms were determined, and the electron dosimetry using these scaling method was evaluated. As a result, it is obviously that dose-distribution in solid phantom can be converted to appropriate dose-distribution in water by means of IAEA depth-scaling.

1. INTRODUCTION

To reduce the uncertainty in the calibration of radiation beams, absorbed dose to water for high energy photons and electrons is recommended as the standards and reference absorbed dose by AAPM Report no.51[1)] and IAEA Technical Reports no.398 (TRS-398) [2)]. In these recommendations, water is defined as the reference medium, however, the water substitute solid phantoms (solid phantoms) are discouraged because they have the largest discrepancies in the determinations of absorbed dose. Nevertheless, when accurate chamber positioning in water is not possible, or when no waterproof chamber is available, solid phantom use is permitted at beam qualities $R_{50} < 4$ g/cm^2 ($E_0 < 10$ MeV) for the electron dosimetry. In the TRS-389, dose-distribution in solid phantom is converted to appropriate dose-distribution in water by means of depth-scaling and fluence-scaling. The depth-scaling is conversion of depth in solid phantom to depth in water. 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

$$z_w = z_{pl}\, c_{pl} \tag{1}$$

where c_{pl} is a depth-scaling factor. The c_{pl} is the ratio of the average depth of electron penetration in water and solid phantom. In addition to depth-scaling, 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 next equation

$$M_Q = M_{Q,pl}\, h_{pl} \tag{2}$$

where h_{pl} is a fluence-scaling factor.
To the best of our knowledge, these two factors have been determined in a few study and factors of only specific phantoms are published in the IAEA Reports[2)]. In this work, the depth-scaling factors and fluence-scaling factors of several commercially available solid phantoms were determined and the electron dosimetry using these factors was evaluated.

2. MATERIALS AND METHOD

2.1 Fundamental physical properties

In this work, WT1 (GAMMEX RMI, Wisconsin, USA), RMI-457 (GAMMEX RMI, Wisconsin, USA), Plastic Water (Nuclear Associate, New York, USA), Virtual Water (Med-Tech, Iowa, USA), WE211[3] (Kyoto Kagaku, Kyoto, Japan), Polystyrene, Polymethyl Methacrylate (PMMA) and MixDP, which as commercially available material, were evaluated. The elemental composition, mass fraction, nominal density and mean atomic number are summarized in Table 1. The mean atomic number $\overline{Z}$ is used for mixtures and/or compounds when comparison of the scaling parameter, and defined as

$$\overline{Z} = \frac{\sum_i \frac{p_i Z_i^2}{M_{A_i}}}{\sum_i \frac{p_i Z_i}{M_{A_i}}} \tag{3}$$

where p_i is the mass fraction, Z_i is the atomic number, and M_{A_i} is the molar mass of element i[4]. The mass stopping powers and density correction factors of solid phantoms were determined according to ICRU Report 37[5,6], and cross section data were prepared using PEGS preprocessor of EGS code system[7].

2.2 Depth-scaling factor: c_{pl}

To convert a depth in solid phantom to a depth in water, several depth-scaling methods have been proposed. In the ICRU Report 35, the linear continuous-slowing-down approximation (csda) range ratio of water to solid phantom was introduced[4]. The csda range accounts for continuous collision and radiative energy losses only. After that it has been cleared that multiple scattering could appreciably affect penetration depths of electrons, the new depth-scaling methods using depth-scaling factor C_{pl}[8] (in the IAEA TRS-381)[9] and c_{pl} (in the IAEA TRS-398)[2] have been proposed. Both C_{pl} and c_{pl} are the ratio of the average depth of electron penetration in water and plastic, nevertheless depth for C_{pl} is defined in unit of cm and depth for c_{pl} is expressed in g cm^{-2}. The c_{pl} is defined as

$$c_{\mathrm{pl}} = \frac{z_{\mathrm{av}}^{\mathrm{water}}\ \rho_{\mathrm{water}}}{z_{\mathrm{av}}^{\mathrm{pl}}\ \rho_{\mathrm{pl}}} \tag{4}$$

where $z_{\mathrm{av}}^{\mathrm{water}}$ and $z_{\mathrm{av}}^{\mathrm{pl}}$ is an average penetration depth (cm) in water and solid phantom, and ρ_{water} and ρ_{pl} is density (g cm^{-3}) of water and solid phantom material, respectively. To calculate z_{av}, EGSnrc version2[10] Monte Carlo code was employed. Monoenergetic electron pencil beam of energies from 1 to 30 MeV have been assumed to impinge normally on finite slab of water and the other materials. The transport of primary electrons has been followed down to the cutoff energy at 10 keV, penetration depths z_i of each history were sampled and z_{av} was calculated.

Table 1 Elemental composition, mass faction, nominal density and average atomic number o water and water substitute solid phantoms.

		Z	A	water	WT1	RMI457	Plastic W	Virtual W	WE211	Polystyrene	PMMA	MixDP
composition and mass fraction	H	1	1.008	0.112	0.081	0.081	0.093	0.077	0.082	0.077	0.081	0.127
	C	6	12.011		0.672	0.672	0.628	0.687	0.663	0.923	0.600	0.763
	N	7	14.007		0.024	0.024	0.010	0.023	0.022			
	O	8	15.999	0.888	0.199	0.198	0.179	0.189	0.207		0.320	0.048
	F	9	18.998									
	Mg	12	24.305									0.036
	Cl	17	35.457		0.001	0.001	0.010	0.001	0.004			
	Ca	20	40.078		0.023	0.023	0.080	0.023	0.022			
	Ti	22	47.880									0.014
	Br	35	79.904				0.000					
density		g/cm³		1.00	1.020	1.030	1.013	1.030	1.017	1.060	1.190	1.0
mean Z				6.6	5.95	5.96	6.62	5.97	5.97	5.29	5.85	5.35

2.3 Fluence-scaling factor: h_{pl}

To convert a reading of ionization chamber in the solid phantom to an appropriate reading in water, the fluence-scaling factor h_{pl} has been proposed in the TRS-389[2]. The h_{pl} is defined as

$$h_{pl} = \frac{M_Q}{M_{Q,pl}} \tag{5}$$

where $M_{Q,pl}$ is a reading of ionization chamber at $z_{ref,pl}$ in the solid phantom and M_Q is a reading at z_{ref} in water. In the identical irradiation condition, absorbed dose to water is D_{water} and absorbed dose to solid phantom is D_{pl}, the ionization charge ratio of Q_{water} in water to Q_{pl} in solid phantom, namely h_{pl} is given by

$$h_{pl} = \frac{Q_{water}}{Q_{pl}} = \frac{D_{water}}{D_{pl}} \left(\frac{s}{\rho} \right)_{pl,\,water} \tag{6}$$

where $(s/\rho)_{pl,\,water}$ is mass collision stopping-power ratio of solid phantom to water. To the best of our knowledge, fluence-scaling factors have been determined in a few experimental works[11, 12]. In this work, the h_{pl}'s were determined by above-mentioned equation and absorbed dose distribution, which calculated using EGS Monte Carlo simulation.

3. RESULTS

3.1 Mass collision stopping power ratio

Figure 1 shows mass collision stopping power ratios of solid phantom to water as a function of electron energy. As compared with other solid phantoms, MixDP has a higher mass collision stopping power ratio, 1.021 to 1.012 for electron energy of 1 to 100 MeV.

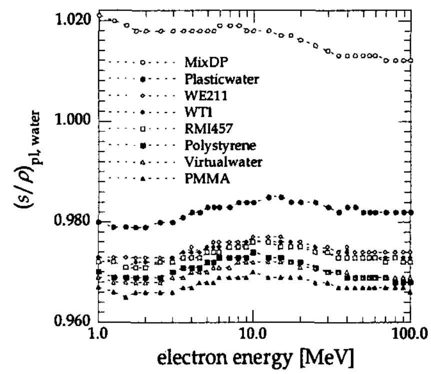

Fig. 1 Mass collision stopping power ration $(s/\rho)_{pl,\,water}$ as a fuction of electron energy.

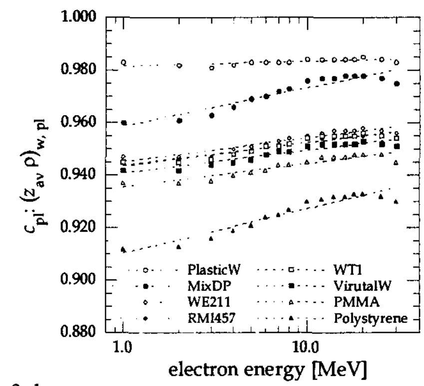

Fig. 2 Depth-scaling factor c_{pl} as a function of electron energy.

3.2 Depth-scaling factor: c_{pl}

Figure 2 shows Depth-scaling factor c_{pl} as a function of electron energy. c_{pl} of Plasticwater is 0.983 for electron energy rage from 1 to 30 MeV, namely, independent of electron energy. MixDP and Polystyrene, which has a lower mean atomic number than water, obviously depend on electron energy. For example, c_{pl} of Polystyrene is 0.912 for 1 MeV and 0.930 for 30 MeV, respectively. However, this depth-scaling method is proposed at beam qualities $R_{50} < 4$ g/cm^2 ($E_0 <$ 10 MeV), and available lowest energy of accelerator is taken into consideration, mean c_{pl} of 6 to 10 MeV were determined. Although c_{pl} is mean value, difference from mean c_{pl} to c_{pl}'s as a function of electron energy is small within 0.3%.

3.3 Fluence-scaling factor: h_{pl}

The fluence-scaling factor h_{pl}'s for several solid phantoms are shown in Table 2. Although h_{pl} slightly depend on electron energy, as the same reasons of depth-scaling factor, h_{pl}'s are determined as a mean value for electron energy range of 6 to 10 MeV.

4. DISCUSSION

Percentage depth dose distributions in water have been compared with distribution in solid phantom with and without scaling. As some results, Figure 3 shows percentage depth dose distributions in water and Polystyrene. It can be seen that depth scaled distribution in Polystyrene using c_{pl} is in good agreement with that in water, although, minor deviations can be observed near the surface and at the end of the electron range.

Table 2 Mean fluence-scaling factors, h_{pl} for solid water substitute materials (E_0 = 6 MeV to10 MeV)

	MixDP	Polystyrene	PMMA	Plasticwater	WE211	Virtual W	WT1	RMI457
This work	1.037	1.035	1.024	0.997	1.019	1.014	1.019	1.011
TRS-398	–	1.026	1.009	0.998	–	–	1.011	1.008

5. CONCLUSIONS

The properties, especially depth-scaling factors c_{pl} and fluence-scaling factors h_{pl} of several commercially available water substitute solid phantoms were determined, and the electron dosimetry using these scaling method was evaluated. As a result, it is obviously that dose-distribution in solid phantom is converted to appropriate dose-distribution in water by means of depth-scaling using IAEA depth-scaling factor c_{pl}.

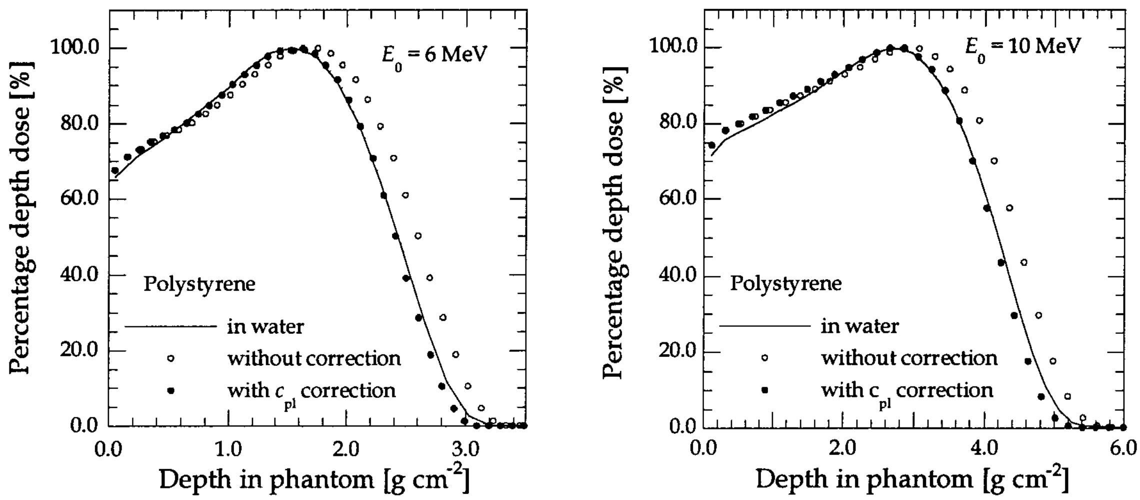

Fig. 3 Comparison of percentage depth dose curve between in pure water, in Polystyrene without correction and with c_{pl} correction.

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