Proceedings of the Tenth EGS4 Users' Meeting in Japan, KEK Proceedings 2002-18, p.55-64

A STUDY ON PROPERTIES OF WATER SUBSTITUTE SOLID PHANTOM USING EGS CODE

H. Saitoh[a], T. Tomaru[b], T. Fujisaki[c], S. Abe[c], A. Myojoyama[a] and K. Fukuda[b]

[a]*Department of Radiological Sciences, Tokyo Metropolitan University of Health Sciences Tokyo, 116-8551, Japan*
[b]*Chiyoda Technol Co., Tokyo, 113-8681, Japan*
[c]*Department of Radiological Sciences, Ibaraki Prefectural University of Health Sciences,Ibaraki,300-0394 Japan*
e-mail: saitoh@metro-hs.ac.jp

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, IAEA Technical Reports no.398 and JSMP Standard dosimetry for radiotherapy 2001. 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 using EGS Monte Carlo simulation. Futhermore, 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)], IAEA Technical Reports no.398 (TRS-398) [2)] and JSMP Standard Dosimetry for Radiotherapy ‘01 (JSMP01)[3)]. 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.

However, almost users in hospitals are confusing because accurate chamber positioning in water is not easy, no waterproof chamber is available and it takes a considerable time that water proof chambers become popular. Therefore 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 and JSMP01. Dose-distribution in solid phantom can be converted to appropriate dose-distribution in water by means of depth-scaling. 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} 5) (in the IAEA TRS-381)6) 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}. In addition to depth-scaling, the reading of ionization chamber $M_{\mathrm{Q,pl}}$ in the solid phantom must be scaled to the appropriate reading M_{Q} in water by fluence-scaling factor h_{pl}.

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 Reports2). In this work, the depth-scaling factors and fluence-scaling factors of several commercially available solid phantoms were determined using EGS Monte Carlo simulation, 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), WE2117) (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

$$\overline{Z} = \frac{\sum_i \frac{p_i Z_i^2}{M_{A_i}}}{\sum_i \frac{p_i Z_i}{M_{A_i}}} \tag{1}$$

where p_i is the mass fraction, Z_i is the atomic number, and M_{A_i} is the molar mass of element i4).

The mass stopping powers and density correction factors of solid phantoms were determined according to ICRU Report 378, 9), and cross section data were prepared using PEGS preprocessor of EGS code system10).

2.2 Depth-scaling factor: c_{pl}

Dose-distribution in solid phantom can be converted to appropriate dose-distribution in water by means of depth-scaling. 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

$$z_{\mathrm{w}} = z_{\mathrm{pl}}\, c_{\mathrm{pl}} \tag{2}$$

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, defined as

$$c_{\mathrm{pl}} = \frac{z_{\mathrm{av}}^{\mathrm{water}}\ \rho_{\mathrm{water}}}{z_{\mathrm{av}}^{\mathrm{pl}}\ \rho_{\mathrm{pl}}} \tag{3}$$

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}, original user code on EGSnrc version2[14) was coded newly. 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. As an example of simulation, Figure 1 shows geometry of simulation and coordinates where primary electrons lost their kinetic energy and came to standstill.

2.3 Fluence-scaling factor: $\mathbf{h_{pl}}$

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 reading of ionization chamber $M_{\mathrm{Q,\,pl}}$ in the solid phantom must be scaled to the appropriate reading M_{Q} in water using the next equation,

$$M_{\mathrm{Q}} = M_{\mathrm{Q,\,pl}}\, h_{\mathrm{pl}} \tag{4}$$

where h_{pl} is a fluence-scaling factor. Namely, when $M_{\mathrm{Q,\,pl}}$ is a reading of ionization chamber at $z_{\mathrm{ref,\,pl}}$ in the solid phantom and M_{Q} is a reading at z_{ref} in water, h_{pl} is defined as

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

To the best of our knowledge, fluence-scaling factors for various materials have been determined in a few experimental works[11-13). In this work, absorbed dose distribution was calculated using EGSnrc and DOSXYZnrc Monte Carlo simulation[14), then the h_{pl}s were determined by next equation. In the identical irradiation condition, when absorbed dose to water is D_{water} and absorbed dose to solid phantom is D_{pl}, h_{pl} is given by

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

where $(s/\rho)_{\mathrm{pl,\,water}}$ is mass collision stopping-power ratio of solid phantom to water.

3. Results

3.1 Mass collision stopping power ratio

Figure 2 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.

3.2 Depth-scaling factor: $\mathbf{c_{pl}}$

Figure 3 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. The mean c_{pl} of several materials are tabulated in Table 2. Although c_{pl} is mean value, difference from mean c_{pl} to c_{pl} as a function of electron energy is small within 0.3% at energy range 6 – 10 MeV. The c_{pl} of this work gave good agreement with the c_{pl} of TRS-389.

3.3 Fluence-scaling factor: h_{pl}

Figure 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 0.5 - 0.8%. The fluence-scaling factors were derived from these absorbed dose ratios $D_{\mathrm{water}}/D_{\mathrm{pl}}$ and above-mentioned $(s/\rho)_{\mathrm{pl,\,water}}$ using equation (6).

Figure 5 shows fluence -scaling factor h_{pl} as a function of electron energy. Although h_{pl} slightly depend on electron energy, as the same reasons of depth-scaling factor, h_{pl} are determined as a mean value for electron energy range of 6 to 10 MeV. The mean h_{pl} (6-10 MeV) of several materials are tabulated in Table 3. The h_{pl} of Plasticwater and RMI457 gave good agreement with that of TRS-389, however, the other materials have a significant difference.

4. Discussion

Percentage depth dose distributions in water have been compared with distribution in solid phantom with and without scaling. As some results, Figure 6 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.

It is difficult to determine the fluence-scaling factor h_{pl} experimentally because of difficulty in accurate chamber positioning and charge storage effect etc. Therefore, h_{pl} were derived from absorbed dose ratios $D_{\mathrm{water}}/D_{\mathrm{pl}}$ which obtained from Monte Carlo simulation and $(s/\rho)_{\mathrm{pl,\,water}}$ in this work. The h_{pl} of Polystyrene was described in detail by Thwaites$^{11)}$. At 7.5 MeV of nominal energy, 1.023 (for NE farmer chamber graphite wall), 1.026 (for NE farmer chamber nylon wall), 1.027 (for NE farmer chamber A-150 wall) and 1.036 (for PTW intra-cavitary) have been reported as h_{pl} of Polystyrene. It is obvious that h_{pl} depend on chamber wall material. For that reason, theoretical equation which takes account of chamber wall have been required to determine h_{pl}.

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 using EGS Monte Carlo simulation and the electron dosimetry using these scaling methods was evaluated. As a result, the c_{pl} of this work gave good agreement with the c_{pl} of TRS-389. And it is obviously that depth in solid phantom is converted to appropriate depth in water by means of depth-scaling using c_{pl}. The h_{pl} of Plasticwater and RMI457 gave good agreement with the h_{pl} of TRS-389, however, the other materials have a significant difference between h_{pl} of this work and that of TRS-389.

Acknowledgment

This work was supported by a specified grant-in-aid of Tokyo Metropolitan University of Health Sciences.

References

1) P. R. Almond, P. J. Biggs, W. F. Hanson et al.: AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams, Med. Phys. **26**(9), 1847-1870 (1999).

2) IAEA: Absorbed dose determination in external beam radiotherapy, -An international code of practice for dosimetry

based on standards of absorbed dose to water-, Technical Reports series No. 398, IAEA, Vienna (2000).

3) JSMP: Standard dosimetry for Radiotherapy, Tsusho-Sangyo Kenkyu-Sha, Tokyo (2002).

4) ICRU: Radiation dosimetry. Electron beams with energy between 1 and 50 MeV, ICRU Report 35 (1984).

5) J. M. Fernandez-Varea, P. Andreo and T. Tabata: Detour factors in water and plastic phantoms and their use for range and depth scaling in electron-beam dosimetry, Phys. Med. Biol. **41**, 1119-1139 (1996).

6) IAEA: The use of plane parallel ionization chambers in high energy electron and photon beams –An international code of practice for dosimetry-, Technical Reports series No. 381, IAEA, Vienna (1997).

7) T. Hiraoka: Dosimetry -Phantom-, Journal of Japan Association of Radiological Physicist **Suppl. 8**, 1-27 (1978).

8) ICRU: Stopping powers for electrons and positrons, ICRU Report 37 (1984).

9) http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

10) W. R. Nelson, H. Hirayama, D. W. O. Rogers: The EGS4 code system, SLAC Report SLAC-265 (1985).

11) D. I. Thwaites: Measurements of ionization in water, polystyrene and a ‘solid water’ phantom material for electron beams, Phys. Med. Biol. **30**, 41-53 (1985).

12) V. M. Tello et al.: How water equivalent are water-equivalent solid materials for output calibration of photon and electron beams?, Med. Pys. **22**, 1177-1189 (1995).

13) A. Nisbet et al.: An evaluation of epoxy resin phantom materials for electron dosimetry, Phys. Med. Biol. **43**, 1523-1528 (1998).

14) I. Kawrakow and D.W.O. Rogers: The EGSnrc Code System, Monte Carlo Simulation of Electron and Photon Transport, NRCC Report PIRS-701 (2001).

Table 1 Elemental composition, mass faction, nominal density and average atomic number of 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/cm^3		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

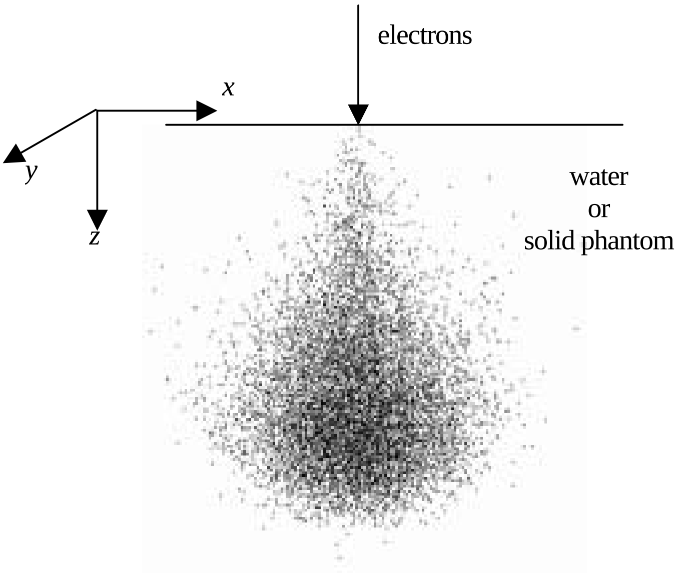


Figure 1 Geometry of z_{av} simulation and coordinates which primary electrons came to standstill

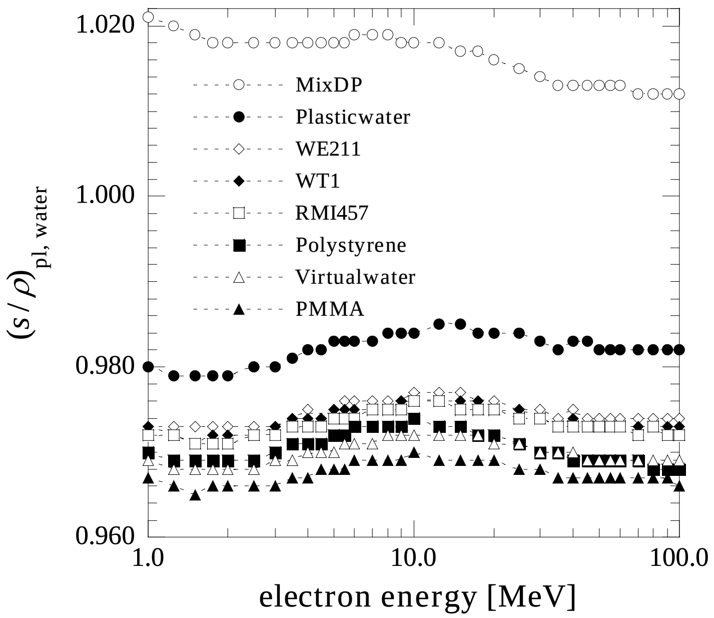


Fig. 2 Mass collision stopping power ration $(s/\rho)_{\text{pl, water}}$ as a function of electron energy.

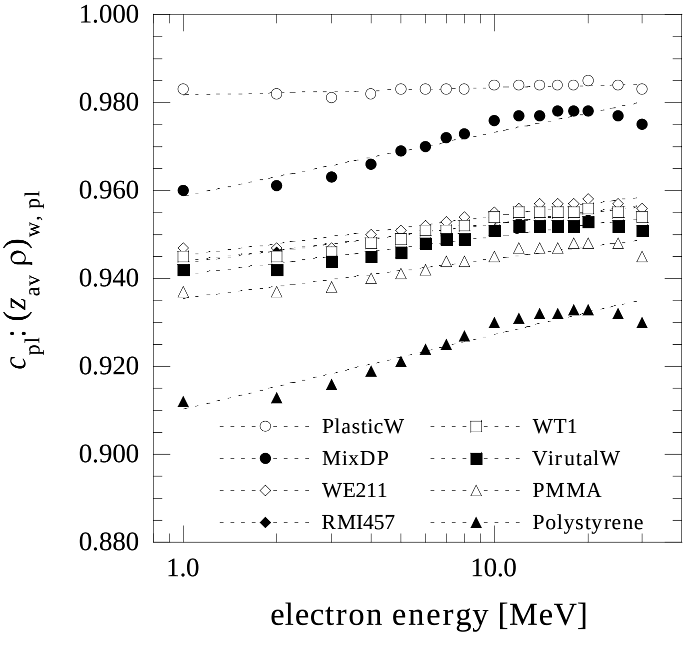
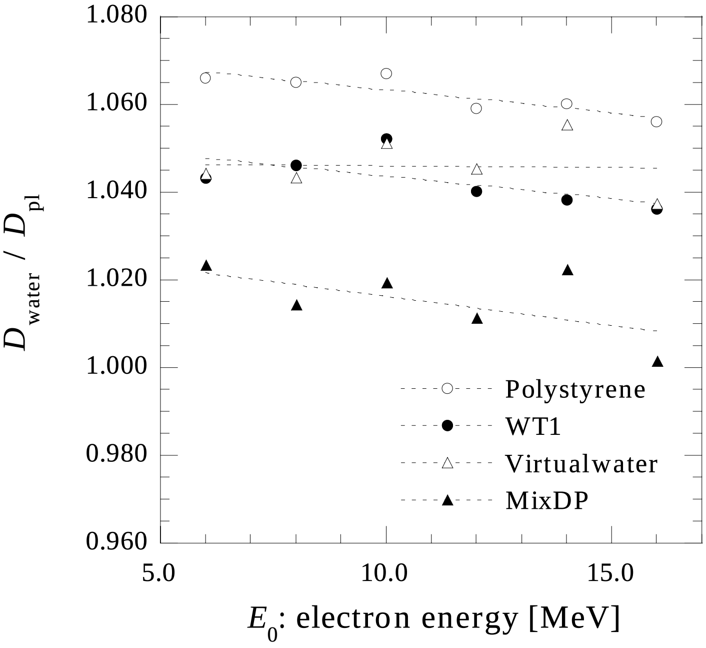


Figure 3 shows Depth-scaling factor c_{pl} as a function of electron energy.

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

Material	MixDP	Polystyrene	PMMA	Plastic W	WE211	Virtual W	WT1	RMI457
This work	0.973	0.927	0.944	0.983	0.954	0.949	0.952	0.952
TRS-398	—	0.922	0.941	0.982	—	0.946	0.949	0.949



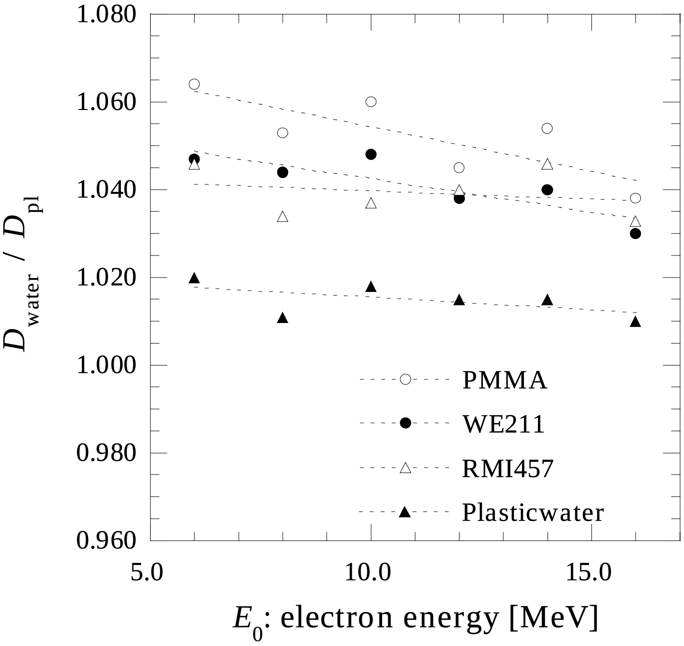


Figure 4 Ratio of absorbed dose at reference depth in water to that in solid phantom D_{water}/D_{pl}.

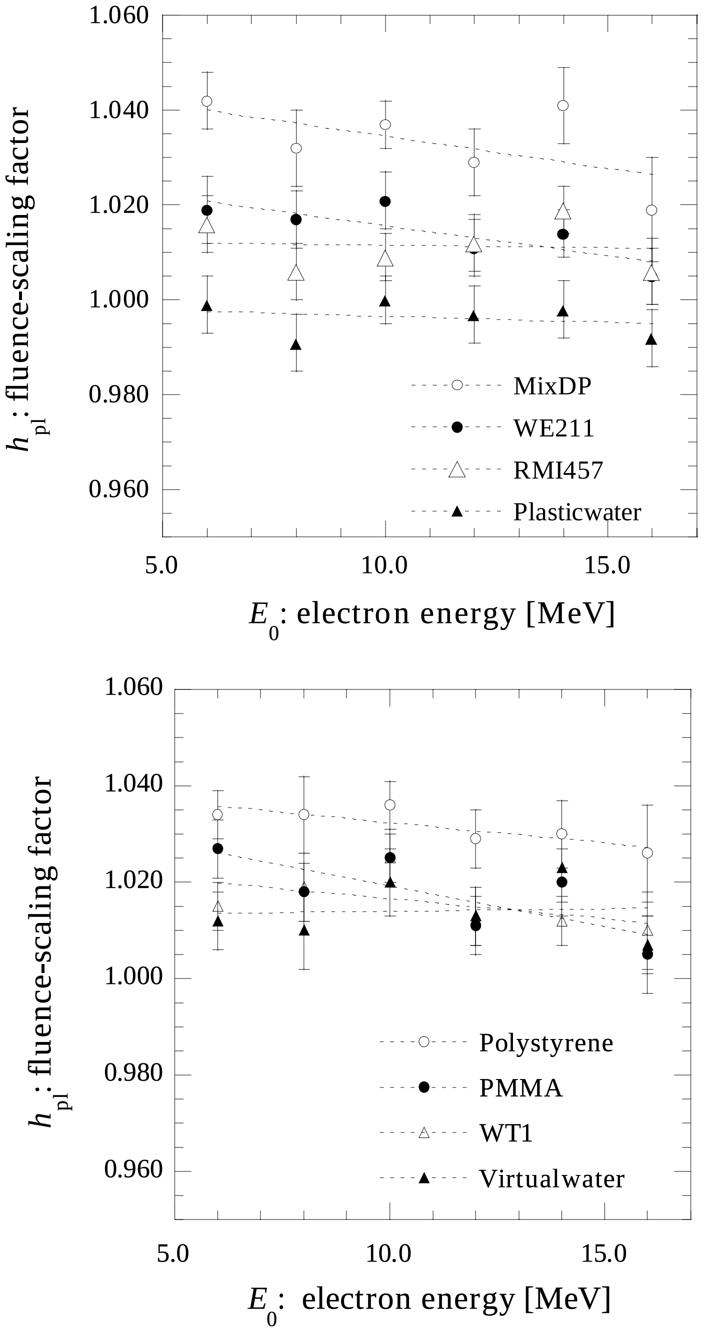
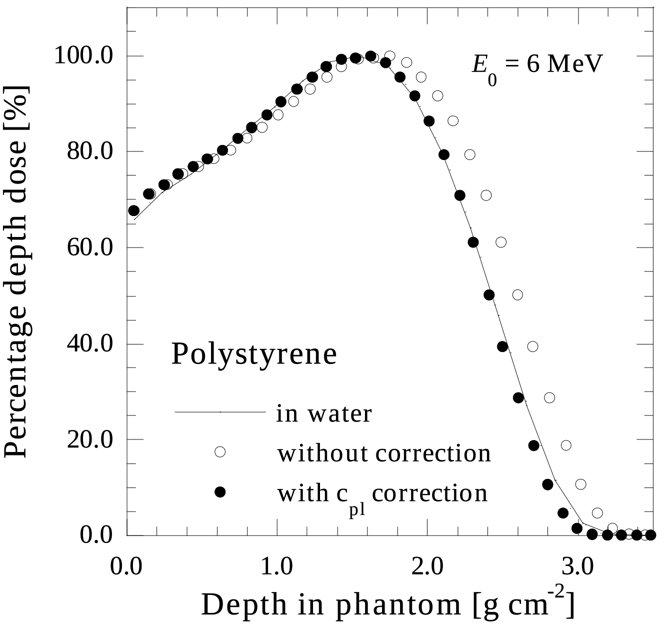


Figure 5 fluence-scaling factors, h_{pl} as a function of electron energy.

Table 3 Mean fluence-scaling factors, h_{pl} for solid water substitute materials ($E_0 = 6$ 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



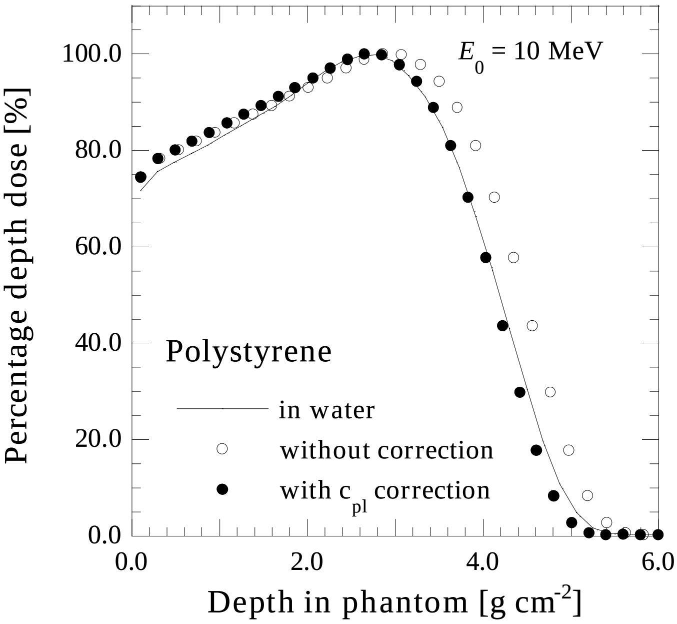


Fig. 6 Comparison of percentage depth dose curve between in pure water, in Polystyrene without correction and with c_{pl} correction.