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Evaluation of water equivalency of Plastic Water™ for high-energy electron beams using IAEA TRS-398 Code of Practice

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Introduction. *In the International Code of Practice for dosimetry TRS-398 published by International Atomic Energy Agency (IAEA), water is recommended as the reference medium for the determination of absorbed dose for high-energy electron beams. Plastic phantoms may be used under certain circumstances for electron beam dosimetry for beam qualities R50 < 4g/cm² (E_0 below 10 MeV). In our study, water equivalency of Plastic Water™ was evaluated in order to determine fluence scaling factors h_{pl} for Plastic Water. Extended set of measurements in water and in Plastic Water were performed.*
Material and methods. *The absorbed dose was determined according to IAEA TRS-398 dosimetry protocol following recommendations for all relevant parameters involved. Water equivalency of Plastic Water was evaluated for five electron beams with nominal energies from 6 MeV to 18 MeV generated by linear accelerator Varian Clinac 2100 C/D. Adequate dosimetry equipment was used throughout the measurements and reference conditions, set by IAEA TRS-398, were followed carefully.*
Results. *The results are presented as ratios D_{pl}/D_w of absorbed dose in Plastic Water and water. Upon the selection of electron energy, the ratios vary from 0.9990 - 1.0058 with combined uncertainties (1SD) of 0.46% - 0.68%. From the measured data, the fluence scaling factors h_{pl} were determined and found to be in the range from 0.9942 to 1.0010. Measurements were taken over a period of 18 months, within the frame of a Coordinated Research Project of the International Atomic Energy Agency.*
Conclusions. *Our results are compatible with previously published data.*

Key words: dosimetry; electron bcams; Plastic Water; IAEA TRS-398

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Introduction

In the International Code of Practice for dosimetry TRS-398 published in the year 2000 by International Atomic Energy Agency (IAEA),[1] water is recommended as the reference medium for the determination of absorbed dose for high energy photon and electron beams. Plastic phantoms should not be used for reference dosimetry in photon beams, however, they can be used for routine quality assurance measurements (daily or weekly output checks), provided a transfer factor between plastic and water has been established. According to IAEA TRS-398 dosimetry protocol, plastic phantoms in the form of slabs may be used under certain circumstances for electron beam dosimetry for the beam qualities $R_{50} < 4$ g/cm^2 (E_0 below 10 MeV); their use is permitted when no waterproof chamber is available or when accurate positioning in water is not possible.

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 and possibly a few others. Several articles comparing the equivalency of various plastics as phantom material to water for electron beam dosimetry have been published.[2-8] 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 our study we evaluated the water equivalency of Plastic Water™ developed by Computerized Imaging Reference Systems Inc. Norfolk, VA, USA, also marketed by Nuclear Associates, Inc. Carle Place, NY, USA. We limited our evaluation only to five electron beams within a range of energies from 6 MeV to 18 MeV. The aim of the study was to determine the energy fluence scaling factor h_{pl} for Plastic Water at the selected five electron energies and to compare this factor to the recommended one in the IAEA TRS-398 dosimetry protocol.

Material and methods

A. Theoretical background

According to IAEA TRS-398 Code of Practice, the calculation of absorbed dose by water $D_{w,Q}(z_{ref,w})$ for high-energy electron beams at the reference depth $z_{ref,w}$ in water, for the reference beam quality Q, and in the absence of the chamber, is given by the equation

$$D_{w,Q}(z_{ref,w}) = M_Q \, N_{D,w,Qo} \, k_{Q,Qo} \quad [1]$$

where M_Q is electrometer reading M_1 corrected for temperature and pressure $k_{T,p}$, as well as for other influencing quantities - polarity k_{pol} and recombination effects k_s. $N_{D,W,Qo}$ is the calibration factor of the selected ionisation chamber in terms of absorbed dose by water in ^{60}Co beam (reference quality Qo), and $k_{Q,Qo}$ is chamber specific factor correcting for the difference between the beam of reference quality Q_o and user quality Q. In TRS-398, electron beam quality is characterized in terms of half-value depth in water R_{50}, which is a depth in water where the absorbed dose in water is 50 % of the maximum absorbed dose. The reference depth $z_{ref,w}$ is also specified by R_{50} and is given by the equation

$$z_{ref,w}(cm) = 0.6 \, R_{50} - 0.1 \quad [2]$$

To determine the absorbed dose in water at $z_{ref,w}$ using a plastic phantom, the reference point of the chamber must be positioned at a scaled reference depth $z_{ref,pl}$ in plastic. For particular beam quality, the measurement depth in plastic expressed in g/cm^2 is obtained from the equation

$$z_{ref,pl} = \frac{z_{ref,w}}{c_{pl}} \quad [3]$$

where c_{pl} is a depth-scaling factor. The c_{pl} is the ratio of the average depth of electron penetration in water $z_{av,w}$ and in plastic $z_{av,pl}$, where these depths are expressed in g/cm^2

$$c_{pl} = \frac{z_{av,w}\rho_w}{z_{av,pl}\rho_{pl}} \quad [4]$$

Additonally to depth scaling, the electrometer reading $M_{Q,pl}$ at the reference depth in plastic $z_{ref,pl}$ must be converted to the equivalent reading $M_{Q,w}$ at the reference depth in water $z_{ref,w}$ using the relation

$$M_{Q,w}(z_{ref,w}) = M_{Q,pl}(z_{ref,pl})h_{pl} \quad [5]$$

where h_{pl} is the fluence scaling factor and is generally energy dependant. The uncertainty associated with this scaling factor is the main reason for avoiding the use of plastic phantoms.

B. Experimental conditions and setup

Experimental equipment

In the study, well guarded waterproof plane parallel ionisation chamber PPC 40 was used together with DOSE 1 electrometer (both produced by IBA Scanditronix - Wellhöfer). The ionisation chamber was calibrated at the IAEA Standard Dosimetry Laboratory in Seibersdorf. The comparison was done for five high-energy electron beams with the energies of 6 MeV, 9 MeV, 12 MeV, 15 MeV and 18 MeV generated by linear accelerator Varian Clinac 2100 C/D. The temperature was monitored with a digital thermometer of the resolution of 0.1°C and the pressure with a digital barometer of resolution of 0.1 mbar.

1D water phantom (produced by MEDTEC) with PMMA walls was used for the measurements in water. The phantom was equipped with a fine mechanical depth adjustment mechanism with the resolution of 0.1 mm. Distilled water was used throughout the measurements.

Table 1. Chemical composition in terms of fractional weight, nominal density ρ[g/cm^3], mean atomic number $\overline{Z}$ and depth scaling factor c_{pl} for Plastic Water. Liquid water data are included for comparison

	Liquid water	Plastic Water
H	0.1119	0.0925
C		0.6282
N		0.0100
O	0.8881	0.1794
Cl		0.0096
Ca		0.0795
Br		0.0003
ρ[g/cm^3]	1.000	1.013
$\overline{Z}$	6.6	6.62
c_{pl}	1.000	0.982

For the measurements in plastic phantom, Plastic Water (cream coloured) in the form of slabs of the size of 30 x 30 cm^2 was used. The thickness of the slabs varied from 1 mm up to 60 mm. Chemical composition (fraction by weight), nominal density, mean atomic number and depth scaling factor for Plastic Water are given in Table 1. For comparison, the data for liquid water are included.

Reference conditions and set-up

Measurements were done in four sessions on four different days. In each session five measurements were done in water as well as in plastic for five high-energy electron beams. Chamber, water and plastic were left in a bunker for several hours before measurements in order to reach as thermal equilibrium. Before we started with measurements in water, the chamber was dipped into water for at least 15 minutes. Reference conditions were always the same: SSD = 100 cm, 10 x 10 cm^2 electron applicator was used and the irradiation time was 200 MU at a constant dose-rate of 300 MU/min. Gantry and collimator were set to 0° and all the measurements were made along the central axis of the beam. Polarising voltage of the chamber was +300 V - the same as during the chamber calibration.

The reference depths were set according to the expressions [2] and [3] for water and plastic, respectively. R_{50} was determined in separate relative dosimetry measurements using a computer controlled water phantom (Blue Phantom made by IBA Scanditronix - Wellhöfer), where the data were collected in 0.4 mm increments. As the thinnest available slab was 1 mm thick, the actual depth of the chamber reference point in plastic was at the depth that was nearest to the calculated one and not exactly at the calculated one. However, the differences were small. As defined in TRS-398 dosimetry protocol, the reference point of the chamber (effective point of measurement) is at the inner surface of the entrance window. Reference depths and some other chamber parameters for selected set of energies are presented in Table 2.

When dipping the chamber into water we were careful not to trap any air bubble at the chamber bottom because it could lower the absorbed dose. For setting up the chamber in plastic, a special cylindrical disc made of white polystyrene was fitted in the chamber hole at its bottom. This was to ensure that no scattered radiation would be lacking due to the absence of scattered material at the chambers bottom. One of the blocks was machined to fit exactly to ionisation chamber PPC40 so that the entrance window of the chamber was at the level of one surface of the block. Under the point of measurement, 6 cm of Plastic Water was always kept to provide an adequate backscatter conditions.

Results and discussion

The results are presented in Table 3 and Figure 1, as the dose ratios Plastic Water/water as a function of nominal beam energy

$$R = \frac{D_{pl,Q}(z_{ref,pl})}{D_{w,Q}(z_{ref,w})} \quad [6]$$

Depending upon the beam energy, the ratios varied from 0.9990 to 1.0058. From the calculated ratios, the fluence scaling factors h_{pl} can be determined.

The measured doses in Plastic Water are within 1% of those measured in water for all electron beam energies, and all the ratios are higher than 1.0 (apart from the ratios for 18 MeV electron beam, where ratios are lower than 1.0). Combined measurement uncertainties (1SD) of type A and type B (detailed explanation about uncertainties is given in reference1), joining the uncertainties from re-

Table 3. Ratios D_{pl}/D_w of absorbed doses measured in Plastic Water and in water for five high energy electron beams produced by Varian Clinac 2100 C/D linear accelerator. Combined measurement uncertainties (1SD) of type A and type B (detailed explanation about uncertainties is given in reference1), joining the uncertainties from repeated measurements from four sessions and estimated uncertainties due to setup and other influencing quantities (pressure, temperature.) Corresponding fluence scaling factors h_{pl} for each electron energy are presented without standard deviations.

	D_{pl}/D_w	h_{pl}
6 MeV	1.0020 ± 0.0068	0.9980
9 MeV	1.0035 ± 0.0050	0.9965
12 MeV	1.0058 ± 0.0046	0.9942
15 MeV	1.0022 ± 0.0061	0.9978
18 MeV	0.9990 ± 0.0053	1.0010

Table 2. Various beam and ionisation chamber (PPC40) parameters used for calculation and measurements of the absorbed dose in water for high energy electron beams generated by linear accelerator Varian Clinac 2100 C/D

	6 MeV	9 MeV	12 MeV	15 MeV	18 MeV
R50 [cm]	2.31	3.54	4.97	6.28	7.58
Rp [cm]	2.91	4.37	6.02	7.54	9.18
$z_{ref,w}^{a}$ [cm]	1.29	2.02	2.88	3.67	4.45
$z_{ref,pl}^{b}$ [cm]	1.31	2.06	2.93	3.74	4.53
$z_{ref,pl}^{c}$ [cm]	1.30	2.10	2.90	3.70	3.50

[a] Reference depth in water of the effective measurement point of the chamber according to TRS-398
[b] Reference depth in Plastic Water of the effective measurement point of the chamber according to TRS-398 obtained from formula expression [3]
[c] Actual depth in PW of the effective measurement point of the chamber due to limitation of minimal slab thickness of 1 mm

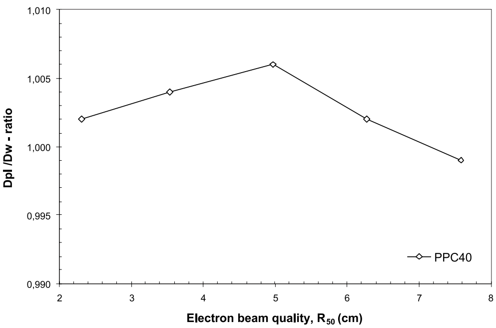

Figure 1. Ratios D_{pl}/D_w of absorbed doses determined with measurements in Plastic Water and in water for five high-energy electron beams - electron beam qualities. Measurements were performed with plane parallel ionisation chamber PPC40. Beam data are in Table 2.

peated measurements from four sessions and the estimated uncertainties due to setup and other influencing quantities (pressure, temperature) are presented in Table 3 and are in the range from 0.46% to 0.68%.

In our study, the average value for h_{pl} for energies below 10 MeV is 0.9973, which is in line with the value published in TRS-398, where h_{pl} is 0.998. Average value of h_{pl} for all electron energies in our study is 0.9975. A slight disagreement with results obtained by Tello *et al.*[5] was observed, but well within the reported uncertainties. We can conclude that our results confirm previously published data for h_{pl} for Plastic Water.

However, we must emphasize, that the temperature of the air in the chamber cavity was probably not the same as the temperature of water when the measurements in water phantom were performed. Due to specific temperature conditions in the accelerators bunker, we could assume that the temperature of the air in the chamber cavity was always at least a little bit higher than the measured water temperature; this, sometimes large difference (up to 3 °C) between the temperature measured in water and the room temperature was due to a slow but permanent rising of room temperature (air condition didn't work optimally). The measured and reported ratios D_{pl}/D_w could thus be too high by up to 0.3%, which corresponds to the temperature difference of 1 °C. As it was not possible to measure actual temperature of the air in the chamber cavity, we included 0.3% of possible temperature variation in the uncertainties of our measurements, rather that in the systematic errors.

We can conclude, that when no water phantom is available in the clinic, or when the use of plastic phantom would be less time consuming or, from any other reason, more appropriate for physicists, the Plastic Water phantom can be used for routine constancy checks of high energy electron beams within the energy range checked in this study and also taking into account the fluence scaling factors as suggested in this study. Even if we take an average fluence scaling factor for all beams in the energy range from 6 MeV - 18 MeV, which is in our case 0.9975, the estimated difference of the absorbed dose determination in Plastic Water should be below 1% comparing to the absorbed dose in water. However, before Plastic Water is to be used as water substitute for reference dosimetry, a careful comparison with measurement in water should be performed.

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