Evaluation of the water-equivalence of plastic materials in low- and high-energy clinical proton beams

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Received 24 September 2016, revised 27 February 2017
Accepted for publication 20 March 2017
Published 13 April 2017

Abstract

The aim of this work was to evaluate the water-equivalence of new trial plastics designed specifically for light-ion beam dosimetry as well as commercially available plastics in clinical proton beams. The water-equivalence of materials was tested by computing a plastic-to-water conversion factor, $H_{pl,w}$. Trial materials were characterized experimentally in 60 MeV and 226 MeV un-modulated proton beams and the results were compared with Monte Carlo simulations using the FLUKA code. For the high-energy beam, a comparison between the trial plastics and various commercial plastics was...
also performed using FLUKA and Geant4 Monte Carlo codes. Experimental information was obtained from laterally integrated depth-dose ionization chamber measurements in water, with and without plastic slabs with variable thicknesses in front of the water phantom. Fluence correction factors, \( k_{fl} \), between water and various materials were also derived using the Monte Carlo method. For the 60 MeV proton beam, \( H_{pl,w} \) and \( k_{fl} \) factors were within 1% from unity for all trial plastics. For the 226 MeV proton beam, experimental \( H_{pl,w} \) values deviated from unity by a maximum of about 1% for the three trial plastics and experimental results showed no advantage regarding which of the plastics was the most equivalent to water. Different magnitudes of corrections were found between Geant4 and FLUKA for the various materials due mainly to the use of different nonelastic nuclear data. Nevertheless, for the 226 MeV proton beam, \( H_{pl,w} \) correction factors were within 2% from unity for all the materials. Considering the results from the two Monte Carlo codes, PMMA and trial plastic #3 had the smallest \( H_{pl,w} \) values, where maximum deviations from unity were 1%, however, PMMA range differed by 16% from that of water. Overall, \( k_{fl} \) factors were deviating more from unity than \( H_{pl,w} \) factors and could amount to a few percent for some materials.

Keywords: water-equivalent plastics, proton therapy, dosimetry, correction factors

(Some figures may appear in colour only in the online journal)

1. Introduction

Water-equivalent plastics offer advantages for dosimetry over the reference material, water, such as the convenience of realizing the experimental setup and better positioning accuracy. As stated in the IAEA TRS-398 Code of Practice (Andreo et al 2000) two steps are involved in the conversion of ionization chamber readings in a plastic phantom to dose to water in a water phantom:

(i) The determination of the range scaling factor, \( c_{ph} \), to convert depth in a plastic phantom to the corresponding depth in a water phantom, and

(ii) The application of a fluence scaling factor, \( h_{pl} \), to convert ionization chamber readings in a plastic phantom to the equivalent reading in a water phantom. While the \( c_{pl} \) factor is calculated by the ratio of continuous-slowing-down approximation (CSDA) ranges in water and in plastic, the \( h_{pl} \) factor is derived from the ratio of ionization chamber readings in water and in plastic at equivalent depths (Andreo et al 2000).

At present, only a limited amount of \( c_{pl} \) and \( h_{pl} \) values are available in the literature because their experimental determination is a time consuming process requiring the acquisition of Bragg peak curves in both the plastic and water, the former involving the insertion of numerous plates one by one to establish the distal edge with sufficient spatial resolution. Therefore, in proton beams, the water-equivalence thickness (WET) is often measured experimentally as an approximation of \( c_{ph} \) where WET values are calculated by the difference of ranges in water, and in water with the material of interest in front. This methodology allows more efficient measuring since ionization chamber readings need to be measured only in water (Moyers et al 1992, Moyers 1999). Zhang et al (2010) compared measured WET values with those
derived analytically in heavy-ion beams. The results obtained showed that analytical methods could well predict experimental values. Palmans et al (2002) conducted a study to measure $h_p$ factors for PMMA with reference to water in 75 MeV and 191 MeV proton beams. For the low-energy beam, measured corrections were smaller than 1% and for the high-energy beam maximum corrections were of the order of 3%. Similar results were obtained by Al-Sulaiti et al (2012) for the water-equivalent plastic PWDT.

Differences in nonelastic nuclear interactions between different elements lead to differences in the fluence in water and low-Z materials such as plastics. Thus, the water equivalence of plastics can also be expressed in terms of the fluence correction factor, $k_f$, which corrects for the differences in fluence. It can also be interpreted as a conversion factor between dose to plastic in a plastic phantom to dose to water in a water phantom (Palmans et al 2002, 2013). Fluence correction factors with reference to water were investigated using Monte Carlo simulations by Palmans et al (2002) for PMMA and polystyrene, by Al-Sulaiti et al (2010, 2012) for A-150, PMMA, PW, PWDT and WT1 and by Lühr et al (2011) for bone and PMMA. Summarizing these findings, fluence corrections were of the order of 1% for low-energy proton beams, while for high-energy proton beams corrections from 2% to 5% were found.

As became evident from these studies, correction factors need to be considered to accurately determine dose to water from measurements performed in a plastic. For high-energy photon and electron beams, White et al (1977), White (1978), White and Tucker (1980) and Constantinou et al (1982) have developed numerous water- and tissue-equivalent plastics such that similar corrections were negligible. The plastics consisted of epoxy resins mixed with low-Z compounds to form a mixture with radiation interaction properties similar to those of water or tissue. Based on this work, WT1 and WTe were designed and commercialised as water-equivalent plastics for high-energy photon and electron beams, respectively. A number of other plastics are currently used in the clinic as water substitutes—Gammex 457-CTG (CTG Solid Water®: Gammex, Middleton, WI, USA), Virtual Water™ (Med-Cal, Middleton, WI, USA), Plastic Water® (CIRS, Norfolk, VA, USA), PMMA and polyethylene, and as tissue substitutes—RANDO® phantom (The Phantom Laboratory, Salem, NY, USA) and A-150 tissue equivalent plastic.

In previous work (Lourenço et al 2016a), three epoxy-resin based mixtures of water-equivalent plastics, specifically formulated for light-ion beams, were experimentally characterized in a high-energy carbon-ion beam. A plastic-to-water conversion factor $H_{pl,w}$ was established and measured as an approximation of $h_{pl}$ using a more practical experimental setup from which WET values could also be derived. In this study, the trial compositions were characterized experimentally in low- and high-energy proton beams, using the previously developed formal framework. Experimental results were compared with Monte Carlo simulations using FLUKA and Geant4. Material physical properties of the trial compositions were calculated and compared to those of water and other commercially available plastics.

2. Materials and methods

2.1. Plastic-to-water conversion factor and fluence correction factor

A formal framework relating ionization chamber measurements in a plastic phantom with dose to water in a water phantom has been described previously (Lourenço et al 2016a) and a brief description is included here.

Three different setups are considered in which ionization chamber readings can be defined: a water phantom (setup 1), a plastic phantom (setup 2) and a water phantom with slabs of plastic in front (setup 3), respectively (figure 1).
As defined in the IAEA TRS-398 Code of Practice (Andreö et al 2000), the fluence scaling factor, $h_{pl}$, is calculated by:

$$h_{pl}(z_{w\text{-eq}}) = \frac{M^{(1)}(z_{w\text{-eq}})}{M^{(3)}(d_{pl})}$$

where $M^{(1)}$ is the ionization chamber reading in the water phantom in setup 1 and $M^{(2)}$ is the ionization chamber reading in the plastic phantom in setup 2. The depth in setup 1, $z_{w}^{(1)}$, is related with depth in setup 2, $z_{pl}^{(2)}$, by the range scaling factor, $c_{pl}$, in units of g cm$^{-2}$. The experimental determination of the range in setup 2, $r^{(2)}$, is very time consuming because for each depth plastic plates need to be added manually in front of the chamber; also its accurate determination is hampered by the resolution of available plates. Thus, a more practical experimental setup was proposed (Lourenço et al 2016a), where measurements are performed in a water phantom with plastic slabs of variable thickness in front of it—setup 3. Ionization chamber readings in setup 3, $M^{(3)}(d^{(3)}, t_{pl})$, are thus a function of the depth in water $d^{(3)}$, and the thickness of the plastic slab $t_{pl}$. The assumption is made that at the interface between the plastic and the water phantom when $d^{(3)} = 0$ and when $z_{pl}^{(2)} = t_{pl}$, $M^{(2)}(t_{pl}) \approx M^{(3)}(0, t_{pl})$. Note that for practical reasons it is not possible to perform measurements at a depth $d^{(3)} = 0$ (due to the water phantom’s entrance wall and the ionization chamber’s front wall), therefore, the most proximal depth is considered. The experimental plastic-to-water conversion factor, $H_{pl,w}^{\text{exp}}$, is thus determined by the ratio of ionization chamber readings in setup 1 and setup 3:

$$H_{pl,w}^{\text{exp}}(t_{pl,w\text{-eq}}) = \frac{M^{(1)}(z_{w}^{(1)})}{M^{(3)}(0, t_{pl})}$$

Depth in setup 1 is related with depth in setup 3 by the range difference, i.e. the water-equivalent thickness of the plastic slab $t_{pl}$: $z_{w}^{(1)} = d^{(3)} + t_{pl,w\text{-eq}}$. Note that the term $t_{pl,w\text{-eq}}$ is equivalent to WET. Furthermore, for one particular slab thickness $t_{pl}$, an $H_{pl,w}$ factor is calculated at every depth $d^{(3)}$ and a mean value can be derived (Lourenço et al 2016a):

$$H_{pl,w}^{\text{exp}}(t_{pl,w\text{-eq}}) \approx \frac{1}{N} \sum_{j=1}^{N} \frac{M^{(1)}(z_{w}^{(1)})}{M^{(3)}(d_{j}^{(3)}, t_{pl})}$$

Points near the Bragg peak are not considered since positioning uncertainties become critical in this region. If equations (2) and (3) give the same result then there is no depth dependence.
on the calculation of $H_{\text{pl,w}}$ for a particular slab with thickness $t_{\text{pl}}$. By testing different slab thicknesses for a given material, a variation of $H_{\text{pl,w}}$ values with depth is determined.

Assuming that between setups 1 and 3, at equivalent depths, (i) the $W_{\text{air}}$ value is the same, (ii) the water-to-air Spencer–Attix stopping power ratio is the same for the fluence $\Phi_{w}^{(1)}$ and $\Phi_{w}^{(3)}$, and (iii) the ionization chamber perturbation factors, $p_{w}^{(1)}$ and $p_{w}^{(3)}$, are also the same, the $H_{\text{pl,w}}$ factor can be calculated using Monte Carlo methods by:

$$H_{\text{pl,w}}^{\text{MC}}(t_{\text{pl,eq}}) = \frac{D_{w}^{(1)}(s_{w,0})}{D_{w}^{(3)}(0, t_{\text{pl}})}$$

(4)

where $D_{w}^{(1)}$ is the dose to water in setup 1 and $D_{w}^{(3)}$ is the dose to water in setup 3. Using similar arguments to those related to equation (3):

$$H_{\text{pl,w}}^{\text{MC}}(t_{\text{pl,eq}}) \approx \frac{1}{N} \sum_{j=1}^{N} \frac{D_{w}^{(1)}(s_{w,0})}{D_{w}^{(3)}(d_{j}, t_{\text{pl}})}$$

(5)

The water-equivalence of plastic materials can also be quantified by calculating the fluence correction factor, $k_{\text{fl}}$. According to Palmans et al (2013), fluence correction factors are calculated by the ratio of fluences differential in energy, $\Phi_{E}$, between water and plastic materials:

$$k_{\text{fl}}^{\text{MC}}(s_{w,0}) = \frac{\int_{0}^{S} \Phi_{E,w,i}(E) \left( \frac{S(E)}{\rho} \right)_{w} \cdot dE}{\int_{0}^{S} \Phi_{E,pl,i}(E) \left( \frac{S(E)}{\rho} \right)_{w} \cdot dE}$$

(6)

where $S/\rho$ is the total mass stopping power and $i$ the charged particle type. While $H_{\text{pl,w}}$ values need to be calculated to convert ionization chamber readings in a plastic phantom to dose to water in a water phantom, $k_{\text{fl}}$ factors are necessary for the conversion of dose to plastic in a plastic phantom to dose to water in a water phantom. Therefore, the water-equivalence of the plastics was also studied by computing $k_{\text{fl}}$ factors with reference to water. Fluence corrections result from the difference in nonelastic nuclear interaction cross sections between different elements. In proton beams, nonelastic nuclear interactions decrease the primary beam fluence and produce secondary particles. The rate of production of these particles is dependent on the medium, thus, the particle fluence in water and plastic at equivalent depths will be different.

### 2.2. Experimental determination of $H_{\text{pl,w}}^{\text{exp}}$

Three plastic materials, referred as plastics #1, #2 and #3, were specifically formulated for light-ion beam dosimetry and characterized experimentally with reference to water in proton beams. The plastics tested were based on the same epoxy resin mixed with different low-Z compounds and were produced in collaboration with St Bartholomew’s Hospital, UK (White et al 1977, White 1978, White and Tucker 1980, Constantinou et al 1982). Experimental information of $H_{\text{pl,w}}^{\text{exp}}$ was obtained from laterally integrated depth-dose ionization chamber measurements in a water phantom using setups 1 and 3 (figure 1). Measurements were carried out at the 60 MeV proton cyclotron at the Clatterbridge Cancer Centre (CCC), UK, and at the 226 MeV proton cyclotron at the Trento Proton Therapy Center (TPTC), Italy (figure 2).
The CCC beam line consisted of a double scattering system and collimators (Kacperek 2009) providing an un-modulated 60 MeV beam with a diameter of 4 mm at collimator exit. Monitoring of the beam was performed with a PTW type 7862 transmission chamber placed in front of the collimator. Measurements were performed in a water phantom with a WET front wall of 3.7 mm, using a Roos plane-parallel ionization chamber (PTW type 34001), placed about 15 cm away from the collimator. The Roos chamber was at a fixed position and the water phantom was moved towards the beam to vary the amount of water upstream of the chamber (constant source-to-detector distance, SDD). This was repeated with different thicknesses of plastic slabs in front of the water phantom. The plastic slabs tested had a surface area of $10 \times 10 \text{cm}^2$ and varying thickness of 0.05 cm, 0.5 cm, 1 cm, 1.5 cm and 2 cm.

At TPTC, the beam line consisted of a scanning system and measurements were performed using a single spot, with 2.7 mm ($1\sigma$) in air at the isocentre (Fracchiolla et al. 2015). Similarly as at CCC, an un-modulated beam was used with a nominal energy of 226 MeV. Measurements were carried out in a water phantom with a front wall of 17.4 mm WET, using a large-area plane-parallel ionization chamber (PTW type 34070 ’Bragg Peak’), and the beam monitor signal for normalization. The water phantom was at a fixed position with its front face aligned with the isocentre and the chamber depth was varied (constant source-to-surface distance, SSD). Measurements were repeated with plastic slabs in front of the water phantom. The plastic slabs tested had a surface area of $10 \times 10 \text{cm}^2$ and varying nominal thickness of 0.05 cm, 1 cm, 2 cm, 4 cm, 6 cm, 10 cm, 14 and 16 cm.

Note that measurements at TPTC were carried out using a constant SSD while at CCC measurements were performed using a constant SDD to avoid corrections for particles scattered by the collimator edges (Kacperek 2009). For the TPTC beam the scattering of particles at the nozzle exit is assumed to be negligible since it consists of a scanning system.

2.3. Numerical simulation of $H_{pl,w}^{MC}$ and $k_{fl}^{MC}$

The $H_{pl,w}^{MC}$ factor was calculated by Monte Carlo simulations using equations (4) and (5) and the fluence correction factor, $k_{fl}^{MC}$, was also calculated using equation (6). Commonly used water-equivalent plastics were also simulated by Monte Carlo. Materials were defined according to IAEA TRS-398 Code of Practice (Andreo et al. 2000) and ICRU Reports 37 (ICRU 1984) and 49 (ICRU 1993), and included A-150 tissue equivalent plastic, PMMA, polyethylene,
polystyrene, Rando® soft tissue (The Phantom Laboratory, Salem, NY, USA), Gammex 457-CTG (CTG Solid Water®; GAMMEX, Middleton, WI, USA) and WT1 (St Bartholomew’s Hospital, London, UK). The density of the trial plastics was determined through weight and volume measurements of each slab.

For the CCC beam, simulations were performed with the FLUKA-2011.2c.4 code (Ferrari et al. 2005, Böhlen et al. 2014). The geometry of the CCC beam line was implemented as described in Bonnett et al. (1993), Baker et al. (2006) and Kacperek (2009). The default HADROTherapy card was used with a delta-ray production threshold set to infinity. Secondary electrons have short ranges so it was assumed their energy was absorbed locally. Inelastic hadron-nucleus interactions were described by the PEANUT (Pre-Equilibrium Approach to Nuclear Thermalization) model (Ferrari and Sala 1998, Battistoni et al. 2006). The incident particles in the first scattering foil were 62.5 MeV protons assuming a Gaussian spread of $\sigma = 0.28$ MeV (Lourenço et al. 2016b). Dose and charged particle fluence differential in energy were scored in bins of 0.01 cm and 0.1 cm in water, respectively, throughout cylindrical phantoms of water and scaled slabs of plastic materials. A total number of $5 \times 10^8$ primary protons were simulated for each material. Scoring was performed within the sensitive radius of the Roos ionization chamber (7.5 mm) and in a larger radius of 10 cm to study the contribution of particles that scatter outside the sensitive area of the chamber. Particles scored included primary and secondary protons, alpha particles, deuterons, tritons and $^3$He ions. In order to implement a constant SDD setup in Monte Carlo, a simulation would be required for each position of the phantom. Therefore, a constant SSD setup was implemented and a correction was applied to obtain SDD calculations (Lourenço et al. 2016b).

Simulations for the TPTC beam were performed using two Monte Carlo codes, FLUKA-2011.2c.4 (Ferrari et al. 2005, Böhlen et al. 2014) and Geant4-9.6.p01 (Agostinelli et al. 2003), because corrections are expected to be higher in high-energy beams. A beam of 226.14 MeV was simulated with a Gaussian energy spread of $\sigma = 0.67$ MeV and divergence of 1.3 mrad (Fracchiolla et al. 2015). Dose and fluence were scored within the sensitive radius of the Bragg peak ionization chamber (40.8 mm) used in the experiments, as well as, within a radius of 10 cm. FLUKA simulations were implemented with similar parameters as those used for the CCC beam. For the Geant4 simulations, the reference physics list QGSP_BIC_EMY was used (Cirrone et al. 2011). Electromagnetic interactions were described by the electromagnetic standard package option 3 (emstandard_opt3), and hadronic nucleon–nucleus interactions were described by the BIC (Binary Cascade) model (Folger et al. 2004). Production thresholds for photons, electrons and positrons were set to 10 km (i.e. secondary production of these particles were not considered in the simulations). Dose and charged particle fluence differential in energy were scored in 0.07 cm slabs in water and scaled slab thicknesses in each plastic material in cylindrical phantoms. For each setup about $4.4 \times 10^6$ primary protons were simulated.

2.4. Material physical properties

To develop a completely water equivalent material one must understand which physical properties are important. For example, the mass stopping power of a specific compound depends on the number of electrons per molecular weight of medium, $Z/A$. Thus, by computing this quantity for different plastic materials and by comparing with those for water, it is possible to quantify the water-equivalence of such materials for a given interaction type. Therefore, $Z/A$ was calculated for all the materials using the Bragg additivity rule for compounds (ICRU 1984), as well as, the scattering length, $X_s$, which is related to the mass scattering power (Gottschalk 2010). The scattering length scales the scattering power for different materials.
and can be interpreted as the distance a 15 MeV proton would have to travel in the medium for the scattering angle to increase by 1 rad (Gottschalk 2010). In addition, the relative water-equivalent thickness (rWET) was calculated experimentally and using Monte Carlo methods for the novel plastics using the following relation:

$$\text{rWET} = \frac{t_{\text{pl,w-eq}}}{t_{\text{pl}}} \quad (7)$$

where $t_{\text{pl,w-eq}}$ and $t_{\text{pl}}$ are expressed in cm. rWET values were also derived from Monte Carlo simulations for seven commercially available plastics. Note that $C_{\text{pl}}$ factors with uppercase are expressed in cm according to IAEA TRS-381 Code of Practice (Almond et al 1997), while $c_{\text{pl}}$ factors with lowercase are expressed in g cm$^{-2}$ according to IAEA TRS-398 Code of Practice (Andreo et al 2000). For a material to be water-equivalent in terms of range, the linear stopping power plays an important role, thus rWET and $C_{\text{pl}}$ values are relevant. On the other hand, for applications where the materials can be scaled by the density, the mass stopping power is important and $c_{\text{pl}}$ is the quantity of interest.

Table 1 lists different material properties computed for various plastics. In comparison to water, $Z/A$ differs 1%-2% for A-150, plastic #3 and Rando soft tissue, whereas for plastic #2 differences were of the order of 4%. In terms of $\rho X_s$ values, plastic #2 was the most water-equivalent material. rWET values were calculated using Monte Carlo methods for ten different thicknesses of each material tested in the TPTC beam and a mean value was derived. FLUKA and Geant4 rWET values agreed within 0.1%, while for the trial plastics characterized experimentally average differences between experimental and Monte Carlo data were about 2%. This discrepancy is partially related to uncertainties in the $I$-values of the plastic materials that influence directly the stopping power and therefore the range. The $I$-values for the novel plastics were calculated based on the Bragg’s additivity rule and the $I$-values were overridden in FLUKA and Geant4 to use the same $I$-value for the same material. Range scaling factors were also computed for comparison. Note that rWET values relate depths between setups 1 and 3, while $C_{\text{pl}}$ and $c_{\text{pl}}$ factors relate depths between setups 1 and 2. A good agreement between rWET and $C_{\text{pl}}$ factors was found for all the materials. In comparison with water, $C_{\text{pl}}$ factors were different by less than 0.5% for WT1 and polyethylene, whereas for A-150 and PMMA differences exceeded 13%-16%. These values suggest that A-150 and PMMA materials would not be suitable for an anthropomorphic phantom. $C_{\text{pl}}$ factors listed in table 1 are in good agreement with those from ICRU Report 49 (ICRU 1993), where for a proton beam of 225 MeV $C_{\text{pl}}$ factors amounted to 1.1345, 1.1583, 0.9982 and 1.0382 for A-150, PMMA, polyethylene and polystyrene, respectively.

3. Results and discussion

3.1. Low-energy beam

Results from $H_{\text{pl,w}}$ and $k_0$ factors are presented as corrections in percentage away from unity i.e. $H_{\text{pl,w}} - 1$ and $k_0 - 1$.

In figure 3, a comparison between experimental data and FLUKA simulations of $H_{\text{pl,w}}$ factors are presented for the three novel plastics. Experimental relative standard uncertainties were obtained by combining type A and type B uncertainties in quadrature and are summarized in table 2. Type A uncertainties included repeatability of the chamber/monitor ratio and type B included uncertainties in temperature, pressure and standard deviation of the mean of $H_{\text{pl,w}}$ obtained from equation (3). At CCC the plastics were tested in the following
chronological order, plastic #3, plastic #1 and plastic #2. As can be seen from table 2, uncertainties decreased significantly with time (from 1.03% to 0.46%) possibly because the beam alignment became more stable. Monte Carlo type-A uncertainties were of the order of 0.2%. Type-B Monte Carlo uncertainties are discussed in section 3.2. For a particular slab thickness $t_{pl}$, a mean value was used to represent the $H_{pl,w}$ factor by application of equations (3) and (5) since there was no obvious trend of variation of $H_{pl,w}$ with depth $(d)^3$ (refer to figure 1).

Overall, corrections were smaller than 0.5% and experimental and Monte Carlo results agreed within uncertainties. These results are in agreement with previous work performed by Palmans et al (2002), where $h_{pl}$ values were measured for PMMA with reference to water in an un-modulated and modulated 75 MeV proton beam. Al-Sulaiti et al (2012) also measured $h_{pl}$ values for the water-equivalent plastic PWDT in a 60 MeV proton beam. Maximum corrections were smaller than 1% at a depth near the Bragg peak. In general, the results from $H_{pl,w}$ and $h_{pl}$ factors indicate no preference regarding the plastic to be used since corrections are small for low-energy beams. These results also confirm the recommendation in IAEA TRS-398 Code of Practice (Andreo et al 2000) for low-energy proton beams where the use of plastic phantoms is permitted for the measurement of dose.

Fluence correction factors between water and the trial plastics were calculated using FLUKA and the results are shown in figure 4, when the fluence of all charged particles is considered. At the surface, fluence corrections are higher in the plastics than in water since $k_{fl}^{MC}$ values are about 0.5% lower than unity. Palmans et al (2013) and Lourenço et al (2016b) reported a similar effect when computing fluence corrections between water and graphite. This effect was mainly attributed to the contribution of alpha particles due to their very short range. Furthermore, the production cross sections of these particles per unit of atomic mass are larger for graphite than for water (ICRU 2000), consequently, the fluence of these particles is larger in compounds with carbon content, such as plastic materials. Fluence corrections did not exceed 1% in absolute magnitude for the three plastics. Monte Carlo calculations of fluence corrections for various plastics were also performed by Palmans et al (2002) using an adapted version of the PTRAN code, by Al-Sulaiti et al (2010, 2012) using MCNPX and FLUKA and by Lühr et al (2011) using SHIELD-HIT10A. All these studies reported corrections below 1% between water and plastic materials in low-energy proton beams.

### Table 1. Material physical properties.

| Material           | $Z/A$ (mol g$^{-1}$) | $\rho X_s$ (g cm$^{-2}$) | $r_{WET}^a$ | $c_{pl}^a$ | $c_{pl}^{ac}$ | Density (g cm$^{-3}$) |
|--------------------|----------------------|---------------------------|-------------|------------|---------------|-----------------------|
| Liquid water       | 0.5551               | 46.9                      | 1.0000      | 1.0000     | 1.0000        | 1.00                  |
| Plastic #1         | 0.5385               | 55.2                      | 0.9352      | 0.9355     | 0.9402        | 0.94                  |
| Plastic #2         | 0.5307               | 46.7                      | 1.0554      | 1.0531     | 0.9534        | 1.05                  |
| Plastic #3         | 0.5449               | 56.4                      | 1.0259      | 1.0278     | 0.9964        | 1.03                  |
| A-150              | 0.5490               | 56.2                      | 1.1332      | 1.1348     | 1.0069        | 1.13                  |
| PMMA               | 0.5393               | 53.8                      | 1.1635      | 1.1645     | 0.9786        | 1.19                  |
| Polyethylene       | 0.5703               | 61.8                      | 0.9958      | 0.9975     | 1.0612        | 0.94                  |
| Polystyrene        | 0.5377               | 59.1                      | 1.0368      | 1.0376     | 0.9789        | 1.06                  |
| Rando              | 0.5446               | 55.2                      | 0.9907      | 0.9915     | 0.9945        | 1.00                  |
| Gammex             | 0.5395               | 53.0                      | 1.0217      | 1.0227     | 0.9806        | 1.04                  |
| WT1                | 0.5395               | 53.0                      | 0.9992      | 1.0002     | 0.9806        | 1.02                  |

$^a$ Values derived from FLUKA Monte Carlo code.
3.2. High-energy beam

Figure 5 shows $H_{pl,w}^e$ factors derived experimentally and calculated using the FLUKA and Geant4 codes for the three novel plastics in the TPTC beam. Open markers represent mean values of $H_{pl,w}^e$ factors (calculated from equations (3) and (5)) and solid markers represent $H_{pl,w}^e$ factors calculated at a specific depth, proximal to $d_0$. For the thinner plastic slabs $t_{pl}$, the data showed no depth dependence on the calculation of $H_{pl,w}^e$ with $d_0$, while for thicker slabs the spread of values was slightly larger. In the following graphs only mean values of $H_{pl,w}^e$ will be presented and discussed (refer to equations (3) and (5)), since its calculation avoids random errors. Similar as in CCC, experimental uncertainties included repeatability of the chamber/monitor ratio, uncertainties in temperature, pressure and standard deviation of the mean of the $H_{pl,w}^e$ factor (table 3). Repeatability was derived from depth-dose measurements only in water that were carried out during the experiments. Uncertainties of 0.5% were found for all the materials.

Figure 3. Plastic-to-water conversion factor measured experimentally (refer to equation (3)) and derived from Monte Carlo simulations (refer to equation (5)) for (a) plastic #1, (b) plastic #2 and (c) plastic #3 in the CCC beam. Open circles represent $H_{pl,w}^e$ measured experimentally and open triangles represent $H_{pl,w}^e$ calculated using FLUKA. Similar results were found for $H_{pl,w}^e$ factors calculated in a larger area. Numerical uncertainty bars are smaller than the marker points.

Table 2. Experimental relative standard uncertainties in the $H_{pl,w}^e$ factor for the measurements performed at CCC.

| Component of uncertainty | Plastic #1 | Plastic #2 | Plastic #3 |
|--------------------------|------------|------------|------------|
|                          | Type A     | Type B     | Type A     | Type B     | Type A     | Type B     |
| Chamber/monitor ratio    | 0.765      | —          | 0.361      | —          | 0.820      | —          |
| Temperature              | —          | 0.050      | —          | 0.050      | —          | 0.050      |
| Pressure                 | —          | 0.050      | —          | 0.050      | —          | 0.050      |
| $H_{pl,w}^e$             | —          | 0.514      | —          | 0.290      | —          | 0.616      |
| Total                    | 0.77       | 0.52       | 0.36       | 0.30       | 0.82       | 0.62       |
| Combined (%)             | 0.92       | 0.46       | 1.03       |

As can be seen from figure 5, experimental data showed no preference regarding the most water-equivalent plastic, with $H_{pl,w}^e$ factors up to 1% from unity. For thicker slabs, FLUKA predicts $H_{pl,w}^e$ factors of about 1% higher than the ones predicted by Geant4. The need for $H_{pl,w}^e$ and $k_0$ factors originates from the differences in the nonelastic nuclear interaction cross sections between water and the different plastic materials. These interactions are described by the PEANUT model in FLUKA (Ferrari and Sala 1998, Battistoni et al 2006), and by
Figure 4. Variation with depth of the fluence correction factors for the three novel plastics with reference to water. Fluence corrections were calculated using Monte Carlo simulations (refer to equation (6)), considering the spectra of all charged particles, inside the area of the Roos chamber used in the experiments.

Figure 5. Plastic-to-water conversion factor measured experimentally and derived from Monte Carlo simulations for (a) plastic #1, (b) plastic #2 and (c) plastic #3 in the TPTC beam. Open markers represent mean values of $H_{pl,w}$ (refer to equations (3) and (5)), and solid markers represent $H_{pl,w}$ factors calculated at a proximal depth of $d^{F}=d^{G}$ (refer to equations (2) and (4)). Circles represent $H_{pl,w}^{MC}$ measured experimentally, triangles and squares represent $H_{pl,w}^{MC}$ calculated using the FLUKA and Geant4 codes, respectively. Numerical uncertainty bars are smaller than the marker points.

the BIC model (Folger et al. 2004) in Geant4. Böhlen et al. (2010) and Robert et al. (2013) compared FLUKA and Geant4 nuclear models for carbon-ion beams and for proton and carbon-ion beams, respectively, and both studies reported substantial deviations between codes. Moreover, ICRU Report 63 (2000) estimated uncertainties of the order of 5%–10% on the total nonelastic cross sections and 20%–30% on the angle-integrated production cross sections for secondary particles in proton beams. Type-B Monte Carlo uncertainties include uncertainties in nuclear cross sections, material data and stopping powers (Lourenço et al. 2016b). We assumed that Type-B Monte Carlo uncertainties on the calculation of $H_{pl,w}^{MC}$ factors are unlikely to be the double that of the average differences between the codes, leading to an estimate of error of 0.54%. Thus, given these uncertainties, Monte Carlo codes do not allow a
further discrimination to be made between the three plastics. Nevertheless, as can been seen from figure 5, maximum plastic-to-water corrections are about 1%.

In figure 6, the water-equivalence of the three plastics tested experimentally is compared with commercially available materials using Monte Carlo simulations. $H_{pl,w}^{MC}$ factors were derived inside the area of the Bragg peak chamber using the FLUKA and Geant4 codes.

For the FLUKA results in figure 6(a), plastic #1 gave the largest correction with reference to water, with an $H_{pl,w}^{MC} − 1$ correction increasing from 0% to 2% at a depth near the Bragg peak. For polystyrene, the $H_{pl,w}^{MC} − 1$ correction increased towards 1.7%, while for polyethylene and PMMA maximum corrections did not exceed 0.5%. The material compositions are C₈H₈ for polystyrene, C₂H₄ for polyethylene and C₅H₈O₂ for PMMA. Thus, carbon, oxygen and hydrogen content influence the rate of variation of the $H_{pl,w}^{MC}$ factor. This is also applied to the other plastics since these elements make up the majority of their compositions. Table 4 summarizes the hydrogen, oxygen and carbon content of the different materials. Polyethylene is the material with highest hydrogen density, followed by A-150 and PMMA, and smaller corrections were found for these materials. For materials with approximately the same hydrogen and oxygen densities, such as, WT1, Gammex 457-CTG, plastic #2 and Rando soft tissue, $H_{pl,w}^{MC} − 1$ corrections increased from 0% toward 1%–1.5%. Plastic #3, which has similar hydrogen content to PMMA, was the most water-equivalent material of the three trial materials tested experimentally. Although on average the plastics in evaluation are composed of 9% hydrogen and 72% carbon (calculated based on the elemental composition by fraction by weight), hydrogen appears to have a larger influence in the calculation of $H_{pl,w}^{MC}$ factors. Previous work from Rasouli et al (2015) reported the issue of quantifying the probability of nonelastic nuclear interactions in compounds with hydrogen content. According to Janni (1982), the probability of a proton undergoing a nonelastic nuclear interaction with hydrogen is zero for the clinical energy range. However, natural hydrogen has a large contribution to the stopping power due to its high $Z/A$ ratio, thus, the total nonelastic nuclear interaction cross section per unit of range is reduced for a compound containing hydrogen.

As with the results presented in figure 5 for the three trial plastics, different corrections were found between Geant4 and FLUKA for the materials commercially available. As shown in figure 6(b), the largest correction was found for A-150 and polyethylene, where corrections increased from 0% toward 1%–1.5% in absolute magnitude. All other materials gave corrections within ±1% in magnitude. Although there are differences in the magnitude of $H_{pl,w}^{MC}$ factors between the two codes, corrections were within 2% from unity for all the materials in this

### Table 3. Experimental relative standard uncertainties in the $H_{pl,w}^{exp}$ factor for the measurements performed at TPTC.

| Component of uncertainty | Plastic #1 Type A | Plastic #1 Type B | Plastic #2 Type A | Plastic #2 Type B | Plastic #3 Type A | Plastic #3 Type B |
|--------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Chamber/monitor ratio    | 0.493             | —                 | 0.493             | —                 | 0.493             | —                 |
| Temperature              | —                 | 0.050             | —                 | 0.050             | —                 | 0.050             |
| Pressure                 | —                 | 0.050             | —                 | 0.050             | —                 | 0.050             |
| $\sigma_{/\mu_T}^{\Sigma}$ | —                 | 0.020             | —                 | 0.030             | —                 | 0.026             |
| Total                    | 0.49              | 0.07              | 0.49              | 0.08              | 0.49              | 0.08              |
| Combined (%)             | 0.50              | 0.50              | 0.50              | 0.50              | 0.50              | 0.50              |
study. Considering the results from the two codes, PMMA and plastic #3 were the materials with smallest corrections, where maximum values were about 1%.

Moyers et al (2011) measured the ratio of ionization chamber readings in water and polystyrene in un-modulated proton beams. For a beam of 200 MeV, corrections were about 0.2% in the plateau region, whereas at the peak, corrections of the order of 2.3% were found. This is a better agreement with the results from FLUKA than with those from Geant4, where maximum corrections at a depth near the Bragg peak were about 1.7% and 0.1%, respectively.

By using the least-squares method, $H_{pl,w}^{MC}$ factors can be approximated by a linear fit as a function of the H, C, O, N, Ca and F content (fraction by weight), considering FLUKA and Geant4 data:

$$H_{pl,w}^{MC} \approx \sum_{k} a_k w_k + (b_k w_k) \cdot z_{w-eq}$$  \hspace{1cm} (8)

where $k$ is the element, $w_k$ is the elemental fraction by weight and $a_k$ and $b_k$ are coefficients as listed in table 5.
As shown in figure 7, the $H_{pl,w}^{MC}$ factors derived using equation (8) and the coefficients listed in table 5 are a good approximation of the data of figure 6. Although there are differences in the magnitude of $H_{pl,w}^{MC}$ factors between the two codes, the relative behaviour of most plastics is similar. However, the parameterisation of $H_{pl,w}^{MC}$ factors as a function of the elemental content did not clarify the source of differences between the codes.

Figure 8 shows the ratio between the energy deposited due to secondary protons inside the radius of the chamber and in a larger radius for water and various materials using FLUKA. Secondary particles originating from nonelastic nuclear interactions emerge with larger angles; therefore a fraction of the energy deposition by these particles is not accounted for within the collecting area of the chamber. Results from figure 8 also illustrate the relative differences in scattering between water and the various plastics. Most plastics in this study showed similar scattering properties to those of water, with the exception of PMMA, A-150 and plastic #1. Consequently, for these materials a discrepancy in $H_{pl,w}^{MC}$ factors calculated inside the chamber area and in a larger area was observed.

$H_{pl,w}^{MC}$ factors derived within a larger area for A-150, PMMA, and the three trial plastics are shown in figure 9. In comparison with the results from figure 6(a) for FLUKA, maximum $H_{pl,w}^{MC}$ values from figure 9(a) were about 0.5% higher for A-150 and PMMA and 0.5% smaller for plastic #1. For Geant4 results in figure 9(b), maximum $H_{pl,w}^{MC}$ values were approximately 0.5% smaller in absolute magnitude for A-150 and plastic #2 in comparison with results from figure 6(b). There were no significant differences between $H_{pl,w}^{MC}$ values calculated within different radii for plastic #3. These results can be compared with experimental $h_{pl}$ values measured by Palmans et al (2002) for PMMA in an un-modulated 191 MeV proton beam. At a depth near the Bragg peak corrections of about 2% were reported. The magnitude of this correction is in better agreement with results from FLUKA, where maximum corrections were of the order of 1.5% than with results from Geant4 data, where maximum corrections were of the order of 0.5%.

Fluence correction factors were also calculated between water and plastic materials using FLUKA and Geant4 inside the area of the Bragg peak chamber (figure 10). As with the results for the CCC beam, at the surface, $k_{fl}^{MC}$ values are about 0.5% lower than unity. This effect is less pronounced for Geant4 results, as previously reported by Palmans et al (2013), where fluence corrections were computed between water and graphite using five different Monte Carlo codes. Plastic #1 showed the largest variation of $k_{fl}^{MC}$ factors with depth, with deviations from unity ranging from −0.8% to 3% in FLUKA and from −0.1% to 2% in Geant4. For A-150 and PMMA, values varied from −1.5% to 1% in FLUKA and from −0.2% to −1.5% in Geant4.

| $k$ | $a_k$ | $b_k$ | $a_k$ | $b_k$ |
|-----|-------|-------|-------|-------|
| H   | 1.00695 | −0.00866 | 1.00907 | −0.00980 |
| C   | 0.99873 | 0.00149 | 0.99938 | 0.00087 |
| O   | 1.00145 | −0.00010 | 1.00145 | −0.00004 |
| N   | 1.03908 | 0.01412 | 1.03917 | 0.01321 |
| Ca  | 0.99625 | −0.00042 | 0.99412 | −0.00006 |
| F   | 0.95212 | −0.04135 | 0.94203 | −0.03719 |

Table 5. Fit coefficients for equation (8) using FLUKA and Geant4 data.
When using FLUKA, polyethylene was the plastic with the smallest variation (−0.5%–0.5%), whilst for Geant4 plastic #3 gave the smallest range of values (−0.1%–0.5%). An interesting observation between figures 6 and 10 is that there is a high degree of correlation between $H_{\text{pl,w}}^\text{MC}$ and $k_{\text{fl,MC}}$, however, there are also distinct differences in their variations with depth. In previous work (Lourenço et al 2016b), fluence corrections were derived between water and graphite by experiments using setups 1 and 3 in a similar way as $H_{\text{pl,w}}^\text{exp}$ factors were measured in this work. The results suggested that secondary particles produced in the slab of material $t_{\text{pl}}$ in setup 3 do not have enough energy to cross the chamber wall; therefore, these particles are not accounted for in the measured value. Fluence corrections measured experimentally...
were thus partial. Note that $k_{\text{fl}}$ values are generally higher than $H_{\text{pl,w}}^{\text{MC}}$. In carbon-ion beams (Haettner et al 2013, Lourenço et al 2016a), secondary particle spectra are mainly from projectile fragmentation and are emitted with sufficient energy to cross the chamber wall and, consequently, $H_{\text{pl,w}} \approx H_{\text{fl}}$.

Lühr et al (2011) performed a Monte Carlo study using the SHIELD-HIT10A code to determine fluence corrections for PMMA in comparison to water in light-ion beams. For high-energy beams, PMMA was shown to be water-equivalent with an uncertainty of 1%. Al-Sulaiti et al (2010) calculated fluence corrections for A-150 and PMMA in a 60 MeV and 200 MeV proton beams using the MCNPX Monte Carlo code and analytical model calculations. Corrections were found to be smaller than 1%. Another study from Al-Sulaiti et al (2012) aimed to study the water equivalence of the following plastic materials: PW, PWDT and WT1. Measurements were performed in a 60 MeV proton beam and compared with Monte Carlo simulations using the FLUKA code for 60 and 200 MeV proton beams. Fluence corrections
were less than 1% for the 60 MeV beam and roughly 3% for the 200 MeV. As evident from these studies and from the results presented here, fluence corrections are energy, material and code dependent. Palmans et al. (2002) estimated fluence corrections for PMMA and polystyrene with reference to water in low- and high-energy clinical proton beams using an adapted version of the PTRAN Monte Carlo code using nonelastic nuclear interaction data from ICRU Report 63 and Janni (1982) tables. They concluded that corrections were dependent on the nuclear data used and that results were inconclusive with regards to the most accurate dataset. Similarly, the work presented here does not allow us to conclude which Monte Carlo method gives a more accurate representation of the experimental data in figure 5.

4. Conclusions

Water-equivalent plastics designed for high-energy photon and electron beams dosimetry are currently also used in proton beams. In this study, the dosimetric water-equivalence of three trial plastics, designed for light-ion beams, as well as, some commercially available plastics was evaluated for proton beams. The water-equivalence was evaluated by computing a plastic-to-water conversion factor, \( H_{pl,w} \), as was previously proposed for carbon-ion beams (Lourenco et al. 2016a). The trial materials were characterized experimentally in 60 MeV and 226 MeV un-modulated proton beams and the results were compared with Monte Carlo simulations. Fluence correction factors, \( k_{fl} \), were also derived using the Monte Carlo method.

For the 60 MeV proton beam, maximum deviations of \( H_{pl,w} \) and \( k_{fl} \) factors from unity were of the order of 1% for all trial plastics. For the 226 MeV proton beam, experimental \( H_{pl,w} \) values were about 1% higher than unity for the three trial plastics and experimental results showed no preference regarding the most water-equivalent plastic. The main reason that low-Z materials—such as phantom materials—are not water-equivalent in proton beams is the difference in the nuclear interaction cross sections between different elements. Different magnitudes of corrections were found between Geant4 and FLUKA for the various materials in consideration because the nuclear data are different depending on the code. These differences are nevertheless consistent with the large uncertainties on nuclear interaction cross sections. Experimental \( H_{pl,w} \) values measured in this work showed no preference with regards to the most accurate dataset, while experimental data from Palmans et al. (2002) and from Moyers et al. (2011) was in better agreement with FLUKA results. Nevertheless, maximum \( H_{pl,w} \) corrections were within 2% for all the materials. Considering the results from the two codes, PMMA and plastic #3 were the materials with smallest \( H_{pl,w} \) corrections, where maximum values were about 1%.

Overall, \( k_{fl} \) factors were higher in magnitude than \( H_{pl,w} \) factors and could amount to a few percent for some materials dependent on the code used. This can have important consequences when comparing dose to water calculated from treatment planning systems to dose to tissue from Monte Carlo simulations.

In summary, the results indicated that plastic #3 and PMMA are the most suitable water-substitutes for the measurement of dose to water using ionization chambers in clinical proton beams, however, PMMA is not water-equivalent when scattering and range are concerned.

Acknowledgments

The authors would like to thank Michael Homer, Nigel Lee and the cyclotron staff at the National Eye Proton Therapy Centre (UK) and at the Trento Proton Therapy Center (Italy) for their assistance during the experiments, Sebastian Galer for technical assistance with FLUKA.
simulations and Simon Duane for useful discussions. The authors acknowledge the use of the UCL Legion High Performance Computing Facility (Legion@UCL), and associated support services, in the completion of this work, and the FLUKA mailing list for all the support with FLUKA code. AL was supported by University College London and the UK National Physical Laboratory through the National Measurement System.

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