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Technical Note

Water equivalence of a solid phantom material for radiation dosimetry applications

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ABSTRACT

Radiological water equivalence of solid phantoms used for radiotherapy is often desired, but is non-trivial to achieve across the range of therapeutic energies. This study evaluated the water equivalence of a new solid phantom material in beam qualities relevant to radiotherapy applications. In-phantom measured depth distributions were compared to that in water to assess the relative attenuation and scatter characteristics of the material. The phantom material was found to be dosimetrically equivalent to water within (1.0 ± 1.0)% for megavoltage photon beam qualities, (1.5 ± 1.3)% for megavoltage electron beam qualities, (1.5 ± 1.5)% for medium-energy kilovoltage X-rays and (3.0 ± 1.5)% for low-energy kilovoltage X-rays.

1. Introduction

Radiological water equivalence is an important quality of solid phantom materials proposed to be used for dosimetric applications that rely on the attenuation and scattering characteristics of water. ICRU Report 44 provides quantification of phantom water-equivalence, describing the phantom as water equivalent if it does not introduce uncertainties greater than 1% in the calculation of absorbed dose [1]. Evaluation of the water equivalence of a material over the range of therapeutic energies used in radiation oncology requires consideration of the interrelated dependence of radiation interaction cross section, energy and atomic composition. At kilovoltage X-ray energies, where the dominant photon interaction is via the photoelectric effect, a small concentration of high atomic number (Z) material can easily alter the absorption properties of a medium due to the Z^3 dependence of the mass attenuation coefficient [2]. At megavoltage energies, where Compton scattering is the dominant interaction, matching the relative electron density (RED) of the material precedes importance over atomic composition to achieve water equivalent attenuation and scattering characteristics. For megavoltage electron energies, equivalence of electron density and atomic composition are required in order to emulate the stopping power and scattering power of water. Due to these complex requirements, it is necessary to characterise the radiation interaction properties of solid phantoms across the range of intended energies before use. Common methods used to assess the water equivalence of materials include a comparison to water via one or a combination of the following: charge collected by an ionisation chamber at an equivalent physical depth [3], percentage depth dose (PDD) [4,5], Hounsfield unit (HU) comparison [4,6], beam profiles [5] and absorbed dose calculation [4,7].

Solid phantoms are widely used in radiotherapy for routine dosimetric quality assurance tests, primarily due to their ease of use compared to scanning water tanks. Solid phantoms are also preferable where precise depth positioning in steep dose gradients is required, and for surface dose measurements. This study evaluated a new solid phantom material, which claims to be manufactured to a higher standard of water equivalency, uniformity and durability than previous models [8]. The material's intended application is for use during radiation therapy quality assurance activities, and thus, was investigated in this context. Some data on the water equivalence of the material is available in megavoltage photon and electron beams [8,9]; however very limited data is currently available at kilovoltage energies, with a single study evaluating water equivalence for brachytherapy applications using Ir-192 [10]. The homogeneity of the material has not been demonstrated previously. This study extends the aforementioned evaluations to include assessment of homogeneity and water equivalence for a complete range of energies in which the material is likely to be utilised as a water-equivalent substitute for radiotherapy quality assurance applications.

2. Material and methods

The solid phantom material under investigation is known by the trade name Solid Water® High Equivalency (HE) (Model number 557,

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Gammex Inc, Wisconsin, USA). It is the next generation of Solid Water® (Model number 457, Gammex/RMI, Wisconsin, USA). The elemental composition of the material was published previously [10]. The sheets used for this study had a surface area of 30 cm × 30 cm, and thicknesses 0.1 cm, 0.2 cm, 0.5 cm, 1 cm and 3 cm.

2.1. Inter- and intra-sheet homogeneity

Electron density homogeneity was evaluated using computed tomography (CT) imaging, by assessing the CT number variation within each sheet, and between sheets. The imaging protocol chosen had a 1 mm slice width to maximise spatial resolution. The sheets were imaged in a stack, with each sheet rotating in position within the stack such that it could be evaluated close to the centre of the scanning field of view, and with sufficient scattering material to avoid imaging artefacts. The average, minimum and maximum CT number of three scans was measured for five regions of interest (ROIs) across the sheet; one central to the sheet and four at the twelve-, three-, six- and nine-o'clock positions, respectively. The regions were chosen to span the primary use areas of the sheets. The ROIs were 9 cm × 9 cm.

Batch uniformity was further investigated by comparing the charge collection of the Advanced Markus (PTW-Freiburg, Germany) parallel plate ionisation chamber when sheets of equivalent thickness were interchanged as build-up material. Combinations of sheets were also evaluated. Sheet thicknesses investigated included 2 mm, 5 mm and 10 mm; the central region of the sheets were evaluated. A minimum of three chamber readings were taken for each measurement set, or until the coefficient of variation of the reading was < 0.5%. Measurements were performed for two kilovoltage beam qualities (HVL 1.04 mm Al and 2.83 mm Cu, see Supplementary Table S1). This energy range was expected to have the highest sensitivity to inter-sheet inhomogeneity, due to the high dependence of mass attenuation coefficient on effective atomic number for photoelectric interactions. This assessment inferred uniformity of atomic composition, assuming there were no substantial electron density changes observed in the previous evaluation.

2.2. Percentage depth ionisation distributions: kilovoltage photons

Depth ionisation distributions were measured in a block phantom (30 cm × 30 cm × 20 cm) constructed of Solid Water® HE and compared to those measured in a water tank. Depth distributions were normalised to a depth of 10 mm. The water equivalence of Solid Water® HE was assessed in four beam qualities, described in Supplementary Table S1. The beams used in this study were generated by an Xstrahl 300 kilovoltage x-ray unit (Xstrahl Limited, Surrey, UK). Depth ionisation distributions were collected for a 10 cm diameter open circular cone for low-energy beams, and a closed-ended 10 cm × 10 cm square applicator for the medium-energy beams. A minimum of three chamber readings were taken at each depth, or until the coefficient of variation of the reading was < 0.5%. This was also the case for measurements collected in Sections 2.3 and 2.4.

The Advanced Markus parallel plate ionisation chamber was used to measure the depth ionisation distributions in both water and Solid Water® HE. Evaluations by Hill et al [11] have confirmed it to be an appropriate chamber for use in kilovoltage beam energies, including at shallow depths. Measurements were performed with the acrylic waterproofing cap on in water, and with the cap off in solid phantom.

A polarity correction (k_{pol}) was applied to measurements, to account for change in chamber reading due to a change in polarising potential. The correction was calculated according to Eq. (1). M_+ and M_- are the electrometer readings obtained with positive and negative polarity, and M is the electrometer reading at the routine polarity (here, −300 V). The polarity correction was determined for all available kilovoltage beam energies at depths 0 mm, 5 mm, 10 mm, 20 mm and 30 mm.

$$k_{pol} = \frac{|M_+| + |M_-|}{2M} \quad (1)$$

2.3. Percentage depth ionisation distributions: megavoltage electrons

Depth ionisation distributions were measured in a block phantom constructed of Solid Water® HE and compared to those measured in a water tank. The water equivalence was assessed for beams of nominal energy 6 MeV and 9 MeV. The beams were generated by a Trilogy linear accelerator (Varian, Palo Alto, USA). Depth ionisation distributions were measured using an Advanced Markus, a well-guarded parallel plate ionisation chamber for the measurement of percentage ionisation distributions in the electron beam energies investigated. The chamber was used with the waterproofing cap for water measurements and cap removed for solid phantom measurements.

Chamber readings were corrected for polarity using Eq. (1). It has been well documented in the literature that parallel plate chambers can exhibit a changing polarity effect with depth in electron beams [12–14]. The polarity correction was determined for depths 1 mm, 10 mm and 30 mm. The correction was extrapolated for larger depths, and an interpolated correction was applied for intermediate depths.

2.4. Percentage depth ionisation distributions: megavoltage photons

Depth dose distributions were measured in a block phantom constructed of Solid Water® HE and compared to those measured in a water tank. The water equivalence was assessed for beams of nominal energy 6 MV and 18 MV. The beams were generated by a Trilogy linear accelerator (Varian, Palo Alto, USA). Depth dose distributions in water and Solid Water® HE were measured using a suitably-characterised parallel plate ionisation chamber, the Roos (PTW-Freiburg, Germany). For solid phantom measurements, the chamber was placed in a Plastic Water® (Computerised Imaging Reference Systems, Norfolk, VA, USA) holder. It has been shown in the literature that Plastic Water® is water equivalent to within 1.0% for this energy range [7]. In the build-up region, Compton current in the collecting electrode was accounted for by averaging depth dose distributions acquired at both negative and positive collecting electrode polarity.

3. Results

3.1. Inter- and intra-sheet homogeneity

For sheet thicknesses > 2 mm, the variation in average CT number between ROIs was < 10 HU. This corresponded to a RED variation of 0.01, calculated according to the HU-RED curve of the CT-scanner (specific to the energy of the scan, 120 kVp). Sheets of thickness ≤2 mm were unable to be quantitatively assessed due to image resolution causing volume averaging effects (image voxel dimension 1.2 mm × 1.2 mm × 1 mm), however qualitative visual assessment of CT images showed no gross inhomogeneities were present. The maximum variation in mean CT number between sheets was (19 ± 10) HU, corresponding to a RED variation of (0.02 ± 0.01). Here, the error bounds indicate 1 standard deviation in the mean. Dosimetrically, the inter-sheet variation corresponded to a (1.0 ± 0.5)% change in measured charge between sheets of the same thickness, for the 1.04 mm Al beam quality. The variation reduced to 0.2% for the HVL 2.83 mm Cu beam quality. The HU and dosimetric evaluations showed correlation; sheets with a higher average CT number were observed to produce a lower chamber reading. The associated uncertainties quoted here account for chamber performance parameters of reproducibility and linearity; the coefficient of variation of each measurement condition was < 0.1% and linearity of the chamber was confirmed to be within 0.5% over the range of charge collection.

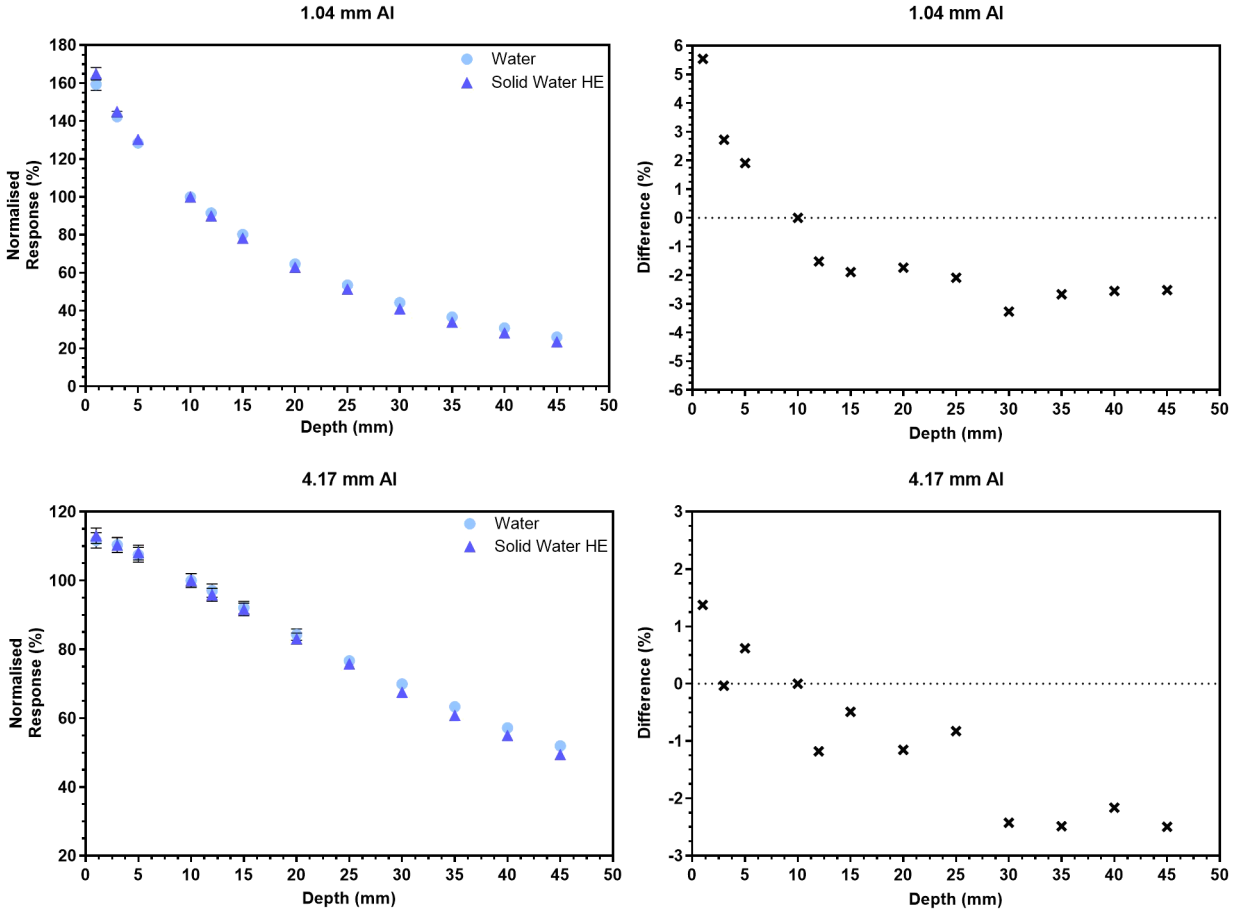

Fig. 1. Percentage depth ionisation profiles for low-energy kilovoltage photon beams, normalised to 10 mm, with corresponding deviation from water on right panel (absolute local difference). Error bars represent the total uncertainty associated with the measurement method. Error bars become no longer visible as depth increases.

3.2. Percentage depth ionisation distributions: kilovoltage photons

Figs. 1 and 2 show that the percentage depth ionisation distributions measured in Solid Water® HE, compared to water, agreed to within 3.2% for the low-energy beam qualities investigated and 1.5% for the medium energy beam qualities investigated (absolute local difference). This was with the exception of the measurement at 1 mm depth for the 1.04 mm Al beam quality, for which the depth ionisation was higher in Solid Water® HE by (5.5 ± 3.3)%.

For all kilovoltage beam qualities, the polarity correction calculated for the Advanced Markus chamber deviated by no more than 0.5% with depth. Hence, no polarity correction was applied to the results shown in Figs. 1 and 2.

The total uncertainty associated with the depth ionisation measurements, considering uncertainty contributions from measurement setup and detector performance, was 1.5% for solid water measurements and 1.1% for measurements in water (see Supplementary Table S2). These uncertainties are indicated by the error bars in Figs. 1 and 2.

3.3. Percentage depth ionisation distributions: megavoltage electrons

The percentage depth ionisation curves for Solid Water® HE, compared to water, as shown in Supplementary Fig. S1, agreed within 1.7% (absolute local difference) for both 6 MeV and 9 MeV beams. The total uncertainty associated with the depth ionisation measurements was 1.3% for measurements in water and solid water, relative to the normalised response at each depth (see Supplementary Table S2).

Note that the polarity correction in Solid Water® HE and water were in agreement to within 0.2% at depth 1 mm and 10 mm, however the correction differed by 0.7% (absolute) at a depth of 30 mm for 6 MeV and 0.5% (absolute) for 9 MeV, with the correction being further from unity in Solid Water® HE.

3.4. Percentage depth ionisation distributions: megavoltage photons

PDD curves for Solid Water® HE compared to water, as shown in Supplementary Fig. S2, agreed within 1.0% for all measured depths, including the build-up region, for both the 6 MV and 18 MV beam qualities. The total uncertainty associated with the PDD measurements was 1.0% for measurements in water and solid water, relative to the normalised response at each depth (see Supplementary Table S2). Compton current contributed minimally in the buildup region, with the PDD differing by no more than 0.5% as the polarity was reversed.

4. Discussion

CT scans showed no substantial manufacturing faults or inhomogeneity. The measured homogeneity of the material indicated little variation in uniformity. The homogeneity of the previous generation of Solid Water® was published by Litzenberg et al [6], however a direct comparison to Solid Water® HE has not been made because of the necessary consistency in imaging protocol required for a reliable comparison. The observed maximum variation in mean CT number between sheets indicated good batch homogeneity. However, the measured homogeneity should be considered as representative only of the batch used for this study – batch to batch variation may exist.

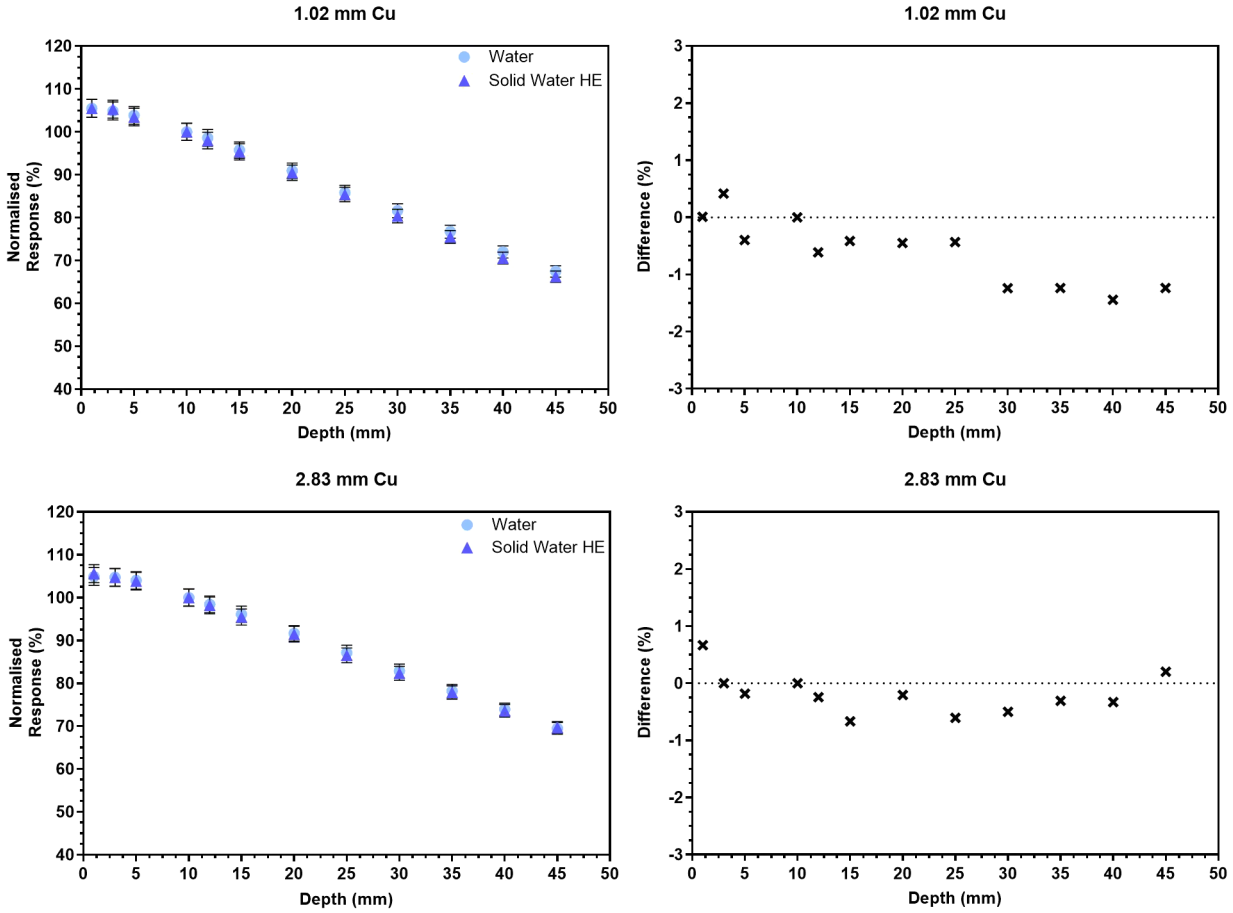

Fig. 2. Percentage depth ionisation profiles for medium energy kilovoltage photon beams, normalised to 10 mm, with corresponding deviation from water on right panel (absolute local difference). Error bars represent the total uncertainty associated with the measurement method.

Depending on the required accuracy of the application, variation between sheets of the same thickness may need to be accounted for, especially where constancy of a parameter is to be evaluated.

Excellent agreement between Solid Water® HE and water depth ionisation distributions was observed for megavoltage electron and photon beams. No differences were observed that would prevent its use as a water-like medium for quality assurance purposes. The results were consistent with those published previously in the literature for megavoltage photons; Araki [9] quoted equivalence to within 0.6% beyond the depth of dose maximum for 4–15 MV photons. For megavoltage photon beams, the material met the definition of water equivalence given in ICRU Report 44 [1] for depths beyond the depth of dose maximum. Schoenfield et al [10] previously reported equivalence to water within 0.8% for the material using an Ir-192 brachytherapy source; the results reported here for medium energy kilovoltage energies are consistent with this level of agreement.

Results of this study showed that, for the range of therapeutic energies considered, the deviation from water increased as the beam energy decreased. This was also observed by Hill et al [5] for a range of alternate solid phantoms, including the original Solid Water®, Plastic Water DT and Virtual Water (Med-Cal, Wisconsin, USA). This relationship is to be expected considering the increasing importance of phantom chemical composition on its attenuation and scatter characteristics as energy decreases. The deviation from a water equivalent response for the low energy kilovoltage beams can be attributed to the increased photoelectric interaction cross section. Considering the Z^3 dependence of the mass attenuation coefficient for photoelectric interactions, the presence of high Z material such as Calcium (Z = 20, weight fraction = 0.0178, elemental composition obtained from Schoenfeld et al [10]) is expected to be a contributing factor.

For the kilovoltage beam energies investigated, the polarity correction determined for the Advanced Markus chamber showed only minor deviation with depth. The absence of depth-dependent polarity effects on ionisation measurements at kilovoltage energies has been shown in the literature [15]. Hence, no polarity correction was applied to the results.

The use of the waterproofing cap for the Advanced Markus chamber may have contributed to the deviation between water and Solid Water® HE seen at the lowest kilovoltage energies. The effect is expected to have a particularly strong effect at shallow depths, for example, the deviation seen in Fig. 1 for 1.04 mm Al beam at 1 mm depth. Although the amount of acrylic build up provided by the cap is small, a substantial non-water equivalence of the material will have the effect of shifting the effective point of measurement of the chamber in water – the impact of which is exaggerated in steep dose gradient regions. The effect of the acrylic cap on water depth dose distributions may be quantified by comparison to Monte Carlo simulations, however this is outside the scope of this work.

Data presented here can be used as a guide to the associated level of uncertainty to be expected when using the material as a water substitute. Solid Water® HE can be considered water equivalent to within 1.7% over a range of therapeutic beam energies from medium energy kilovoltage to megavoltage, and 3.2% for the low energy kilovoltage range. The phantom material will likely find useful application for

collecting machine-specific PDDs for kilovoltage energies. In megavoltage electron and photon beam qualities, it is expected to lend itself to routine QA applications where use of a water-equivalent phantom is desirable (although not strictly necessary) such as for output constancy, energy constancy and/or field output factor constancy measurements.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Uncertainties contributing to depth ionisation data originating from measurement setup and detector performance have been considered, with individual sources of error added in quadrature to form the total uncertainty estimate for each beam type. This is consistent with recommendations provided by the Guide to the expression of Uncertainty in Measurement (GUM) [16]. Components contributing to the total uncertainty are shown in Supplementary Table S2. The uncertainty associated with depth ionisation distributions in water were of the same magnitude as for the solid phantom, with the exception of the contribution of sheet inhomogeneity for the kilovoltage energies. In this case, the total combined uncertainty was 1.1% for water. The uncertainties indicated by the error bars in Figs. 1 and 2 and Supplementary Figs. S1-2 are reflective of the uncertainties shown in Supplementary Table S2, and have been presented as relative to the respective normalisation depth.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.phro.2020.05.003.

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