Available online at www.sciencedirect.com
ScienceDirect
Radiation Measurements 43 (2008) 1258–1264
Radiation Measurements
www.elsevier.com/locate/radmeas

Evaluation of the water equivalence of solid phantoms using gamma ray transmission measurements

R.F. Hill[a,b,*], S. Brown[a,c], C. Baldock[a]

[a]Institute of Medical Physics, School of Physics, University of Sydney, Australia
[b]Department of Radiation Oncology, Royal Prince Alfred Hospital, Sydney, Australia
[c]Department of Radiation Oncology, Royal North Shore Hospital, Sydney, Australia

Received 14 September 2007; received in revised form 6 January 2008; accepted 23 January 2008

Abstract

Gamma ray transmission measurements have been used to evaluate the water equivalence of solid phantoms. Technetium-99m was used in narrow beam geometry and the transmission of photons measured, using a gamma camera, through varying thickness of the solid phantom material and water. Measured transmission values were compared with Monte Carlo calculated transmission data using the EGSnrc Monte Carlo code to score fluence in a geometry similar to that of the measurements. The results indicate that the RMI457 Solid Water, CMNC Plastic Water and PTW RW3 solid phantoms had similar transmission values as compared to water to within ±1.5%. However, Perspex had a greater deviation in the transmission values up to ±4%. The agreement between the measured and EGSnrc calculated transmission values agreed to within ±1% over the range of phantom thickness studied. The linear attenuation coefficients at the gamma ray energy of 140.5 keV were determined from the measured and EGSnrc calculated transmission data and compared with predicted values derived from data provided by the National Institute of Standards and Technology (NIST) using the XCOM program. The coefficients derived from the measured data were up to 6% lower than those predicted by the XCOM program, while the coefficients determined from the Monte Carlo calculations were between measured and XCOM values. The results indicate that a similar process can be followed to determine the water equivalency of other solid phantoms and at other photon energies.

Keywords: Solid phantoms; Water equivalency; Technetium-99m; EGSnrc Monte Carlo; XCOM; Low energy photons

1. Introduction

Solid water equivalent phantoms are used extensively for the dosimetry of photon and electron beams as used in radiation therapy, radiology, nuclear medicine and radiation safety. Water is the phantom material of choice for both reference and relative dosimetry measurements in radiation therapy. There are situations where a solid phantom is required (Andreo et al., 2000; Badhwar et al., 2002; Metcalfe et al., 1997). Many radiation detectors are not waterproof in which case a solid phantom must be used (Mitchell et al., 1998). A solid phantom can be designed into the required shape and/or size. In addition, measurements within high dose gradients can be difficult to perform in water (Demir et al., 2005; Williams and Thwaites, 2000). Solid phantoms are also more useful for routine measurements since they tend to be more robust and easier to set up than water phantoms.

For a solid phantom to be considered water equivalent, it must have similar radiological properties as that of water. These properties include physical density, relative electron density and effective atomic number as well as similar absorption and scattering of radiation (Andreo et al., 2000; ICRU, 1989). For higher energy photon beams as used in megavoltage radiotherapy beams, the dominant interaction process is the Compton effect, which has a dependence on the electron density of the medium. The photons produced by therapeutic kilovoltage X-ray units and some brachytherapy sources are lower in energy and the photoelectric effect becomes a more dominant

---

[*] Corresponding author at: Department of Radiation Oncology, Royal Prince Alfred Hospital, Missenden Road, Camperdown, NSW 2050, Australia.

E-mail address: robin.hill@email.cs.nsw.gov.au (R.F. Hill).

1350-4487/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.radmeas.2008.01.019

interaction processes. The photoelectric effect has a strong dependence on the atomic number of the medium. This means that at these lower energies, differences in the effective atomic number of the solid phantom as compared to water may lead to greater differences in measured dose.

The ICRU Report 44 recommends if any solid phantom is to be considered water equivalent, it should not introduce uncertainties to the absorbed dose of greater than 1% otherwise correction factors may be required (ICRU, 1989). Testing the radiological tissue equivalence in terms of the water equivalency of a solid phantom for X-rays with lower energies can be achieved by several methods: measurement of relative dosimetry data such as percentage depth doses and output factors (Allahverdi et al., 1999; Healy et al., 2005; Hill et al., 2005), measurement of X-ray beam attenuation and/or back scatter factors (Hermann et al., 1985), measurement of X-ray linear attenuation coefficient, μ, using radioisotopes (Midgley, 2005) and Monte Carlo dose calculations (Meigooni et al., 1994; Reniers et al., 2004).

The results presented by Hermann found that the solid RW1 phantom material had good agreement with water for both transmission and backscatter measurements in the energy range 10–100 kV (Hermann et al., 1985). The epoxy resin material, Plastic Water, has been shown to give significant dose differences as compared to water for X-rays with energies less than 100 keV (Hill et al., 2005; Meigooni et al., 1994). These studies also found that the doses measured using the RMI457 Solid Water epoxy resin phantom had good agreement with the doses measured in water even at the lower energies.

Midgley measured the X-ray linear attenuation coefficient, μ, for a number of low atomic number materials using a technetium-99m source and characteristic radiation in the energy range of 32.1– 62.2 keV (Midgley, 2005). The difference in μ, between Perspex and water, was up to 14% but for the WT1 solid phantom, the maximum difference in the coefficient was 3.6% over the same energy range.

In this paper, we used gamma ray transmission measurements in solid phantoms to investigate the radiological water equivalency of these phantoms. Linear attenuation coefficients were determined for the solid phantoms and water using transmission curves and compared with Monte Carlo calculations and standard published data. An assessment of the dosimetric response of the solid phantoms as compared to water was made.

2. Materials and methods

2.1. Experimental methods

All measurements were performed using a technetium-99m radionuclide which has a half-life of 6.01 h (Chu et al., 1999). Technetium-99m emits a number of different gamma and beta rays while undergoing radioactive decay. The main gamma ray emissions have energies of 140.5 and 142.6 keV with relative amounts of 98.6% and 1.4%, respectively (Chu et al., 1999). It is also noted that characteristic X-rays and Auger electrons are emitted after internal conversion events and are not considered in this work.

Table 1
Elemental composition by relative weight and physical density of the five phantom materials used in this study: Water, RMI457 Solid Water (RMI Gammex), Plastic Water (Computerized Imaging Reference Systems), RW3 solid phantom (PTW Freiburg) and Perspex

	Water	RMI457	Plastic Water	RW3	Perspex
H	0.1119	0.0809	0.0925	0.0759	0.0805
C	–	0.6722	0.6282	0.9041	0.5998
N	–	0.0240	0.0100	–	–
O	0.8881	0.1984	0.1794	0.0080	0.3996
F	–	–	–	–	–
Cl	–	0.0013	0.0096	–	–
Ca	–	0.0232	0.0795	–	–
Br	–	–	0.0003	–	–
Ti	–	–	–	0.0120	–
Physical density ρ (gm cm^{-3})	1.000	1.030	1.013	1.045	1.190

The following phantom materials were used in the comparison: water, Solid Water RMI457 (RMI Gammex, Middleton, WI, USA), Plastic Water (Computerized Imaging Reference Systems Inc., Norfolk, VA, USA), RW3 Solid Water (PTW Freiburg, Freiburg, Germany) and Perspex. The Plastic Water and RMI457 Solid Water are made from epoxy resins. Table 1 shows the elemental composition and physical characteristics of each of the phantom materials (Andreo et al., 2000). The solid phantom materials were in the form of blocks with dimensions of at least $20 \times 20\,\text{cm}^2$ and different thicknesses. The specified thickness of each block used was verified using a vernier calliper and agreed to within ±0.2 mm.

For each phantom material, μ, for the 140.5 keV gamma ray was determined using the Bouger–Lambert–Beer law which states that the intensity of the gamma rays, I, is given by the following equation (Johns and Cunningham, 1983):

$$I = I_0 \times \exp(-\mu x), \tag{1}$$

where I_0 is the intensity of the primary beam and x is the thickness of the phantom material.

The radionuclide source was located inside a custom designed lead container that produced narrow beam geometry with a beam diameter of 0.5 cm (Brown et al., 2005). The geometry of the set-up used for the measurements is shown in Fig. 1. A Philips SkyLight SPECT gamma camera (Philips Medical, North Milpitas, CA, USA) using the Skylight software recorded the total number of photons detected. The gamma camera was positioned so that it was facing towards the floor. The lead container with the source was placed on the floor and aligned with the head of the gamma camera, which was 1 m above the container. The attenuating material was placed 10 cm above the source and aligned to be perpendicular to the beam. The gamma camera had an energy window set to ±5% of the main gamma ray energy of 140.5 keV in order to remove low energy scattered photons from the total number of counts (Jaszczak et al., 1984).

Photons were counted for 60 s for each measurement. For each phantom material, the initial intensity, I_0, was measured with nothing in the beam, followed by measurements with

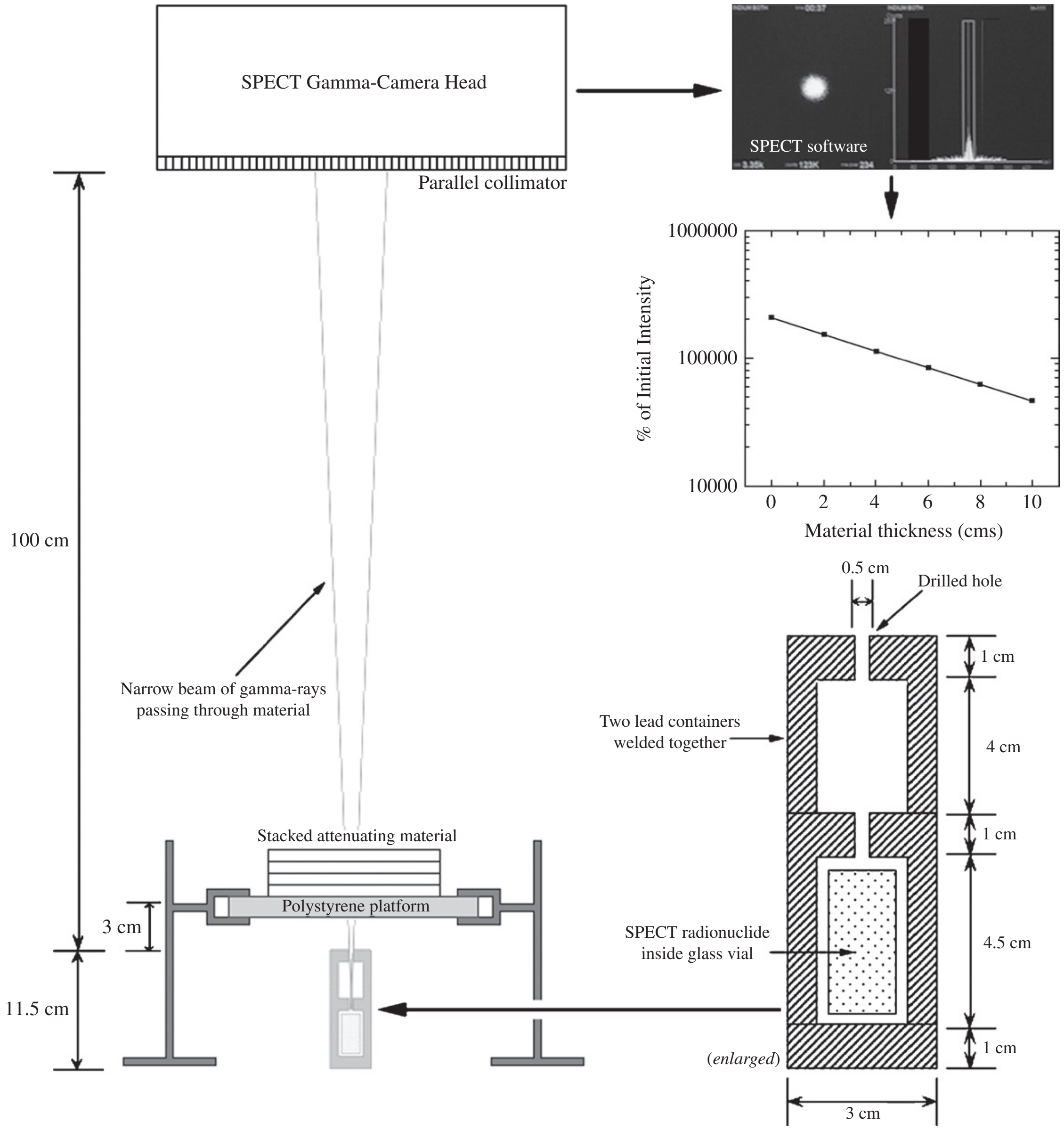

Fig. 1. A diagram of the equipment used to measure the transmission values for technetium-99m gamma rays passing through varying thicknesses of five phantom materials. Shown are the lead container that held the radionuclide, the gamma camera and the support for the different phantom materials.

different thickness of the phantom material from 2 to 10 cm. The water was held in a thin plastic container, which was included in all transmission measurements through water and include for the initial intensity, $I_{0.}$

Due to the short half-life of the technetium-99m isotope, corrections were applied to take into account radioactive decay during the experiment. The correction factor to the total number of counts is given by δ as per the following equation:

$$\delta = \exp\left(\frac{-t \times \ln(2)}{t_{1/2}}\right), \tag{2}$$

where t is the time from the measurement of the initial intensity and $t_{1/2}$ is the half-life of the source.

The error for each measurement was determined from the uncertainty in the phantom thickness and the estimated uncertainty from Poisson statistics.

2.2. Monte Carlo methods

Monte Carlo methods are widely used in solving radiation dosimetry problems. In this work, we used the Electron Gamma Shower (EGSnrc) version 4.2 Monte Carlo code to simulate the gamma rays incident on the different phantom materials (Kawrakow, 2000). The FLURZnrc user code was used to calculate the energy fluence of the radiation beam for a cylindrical geometry (Rogers et al., 2000).

The EGSnrc code is able to model the photoelectric effect, Compton scattering and Rayleigh scattering interaction processes that occur for these photon energies. There are a number of calculation options that were ‘switched on’ in the software for all calculations: the inclusion of bound Compton scattering, angular sampling of the direction of the emitted photoelectron, Rayleigh scattering, atomic relaxations and electron spin effects. The use of these parameters for our calculations is consistent with the results of a previous study (Verhaegen, 2002). Photon and electron energy cut-off parameters (including the electron rest mass), PCUT and ECUT, were set to values of 0.002 and 0.561 MeV, respectively, for all calculations. These cut-off parameters determine when a photon or electron is no longer simulated and the energy is deposited in the local voxel.

The technetium-99m source was modelled in FLURZnrc as a narrow parallel beam, with a diameter of 0.5 cm, which corresponds to the size of the beam used in the measurements. The source was simulated as a monoenergetic beam of photons with energy of 140.5 keV. It should be noted that the lead container holding the source was not explicitly modelled in the Monte Carlo simulations. The slab of phantom material was positioned at a distance 10 cm from the source. The total photon fluence was scored in air within a 1 mm thick and 15 cm diameter voxel situated on the central axis and at 1 m distance from the start of the attenuating phantom, with large diameter of the voxel selected to be much larger than the radial dimension of the incident radiation beam. The thickness of the phantom material was varied, matching the thickness of the phantoms used in the measurements. Photons in this voxel were scored into different energy bins in the range of 0–145 keV with increments of 5 keV. The calculation of transmitted primary photons was determined from the tally of photons in the top energy bin of 140–145 keV.

The EGSnrc code uses cross section data from a data file created by the PEGS4 application. There were two options for cross section data to be used by PEGS4 to generate the PEGS4 data file: (1) the default setting which photon cross section data derived by Storm and Israel and (2) newer National Institute of Standards and Technology (NIST) cross-section data (Kawrakow, 2000). The NIST data set contains newer cross-section data that is applicable at lower photon energies. Fluence calculations were performed using each of the cross-sectional data sets. To minimise the calculation uncertainty in FLURZnrc, a large number of incident photons were used for each calculation set: 2×10^7.

2.3. Determination of linear attenuation coefficients

The narrow-beam μ, for each material was determined using curve fitting software within the Sigmaplot software program (Systat Software Inc., San Jose, California) using an exponential function as per Eq. (1). The resulting output provides a value of μ, and a calculated standard error. There were three μ's determined for each of the phantom materials:

- Measured linear attenuation coefficient, μ_{measured}, based on the corrected counts recorded by the gamma-camera against the thickness of attenuating material.
- Monte Carlo calculated linear attenuation coefficient, μ_{EGSnrc}, using the transmission data from the Monte Carlo calculations.
- Calculated linear attenuation coefficients using data provided by the NIST via their online XCOM data base found at http://physics.nist.gov/PhysRefData/Xcom/Text/XCOM.html (Berger et al., 1998). The formulation for each material was taken from Table 1 and used as an input in the XCOM database, to give the total mass attenuation coefficient at photon energy of 140.5 keV. The total linear attenuation coefficient was determined from this by multiplying by the physical density of the material as given in Table 1.

3. Results and discussion

The maximum uncertainty in the measured counts was calculated to ±0.8% based on geometrical uncertainties and variations in the number of counts detected by the gamma camera. The uncertainty in the phantom thickness was determined to be ±0.05 cm for the solid phantoms and ±0.1 cm for the water.

The measured transmission values as a function of phantom thickness, based on the corrected counts of gamma rays, are presented in Fig. 2. The results indicate that the transmission through Plastic Water, RMI 457 Solid Water and RW3 phantoms are in close agreement to that through water. The agreement was in most cases within 1% and a maximum deviation of 1.5%. This level of agreement between doses measured in solid phantoms and in water is similar to previous work using megavoltage X-ray beams (Allahverdi et al., 1999; Liu et al., 2003) and in Monte Carlo calculations at similar photon energies for brachytherapy sources (Meigooni et al., 1994). The transmission values through Perspex are less than those for water and with a greater deviation, being up to 4% at depth.

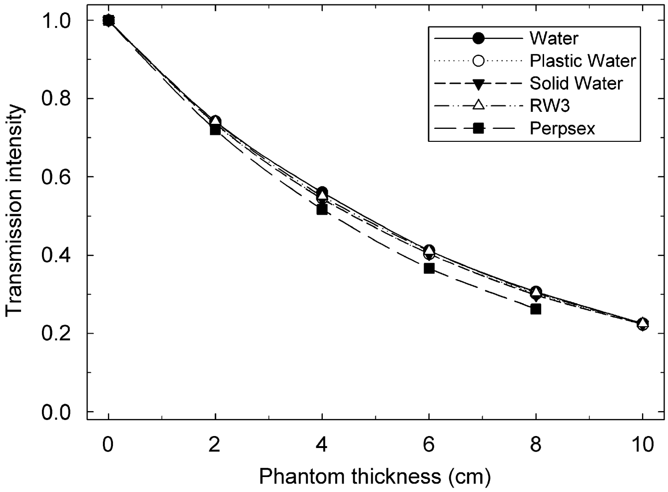

Fig. 2. A comparison of measured transmission values of technetium-99m gamma rays passing through varying thicknesses of 0–10 cm of five phantom materials. The measurements were done at the thicknesses indicated by the symbols on the plots. The lines passing through the data points have been applied for ease of reading the data.

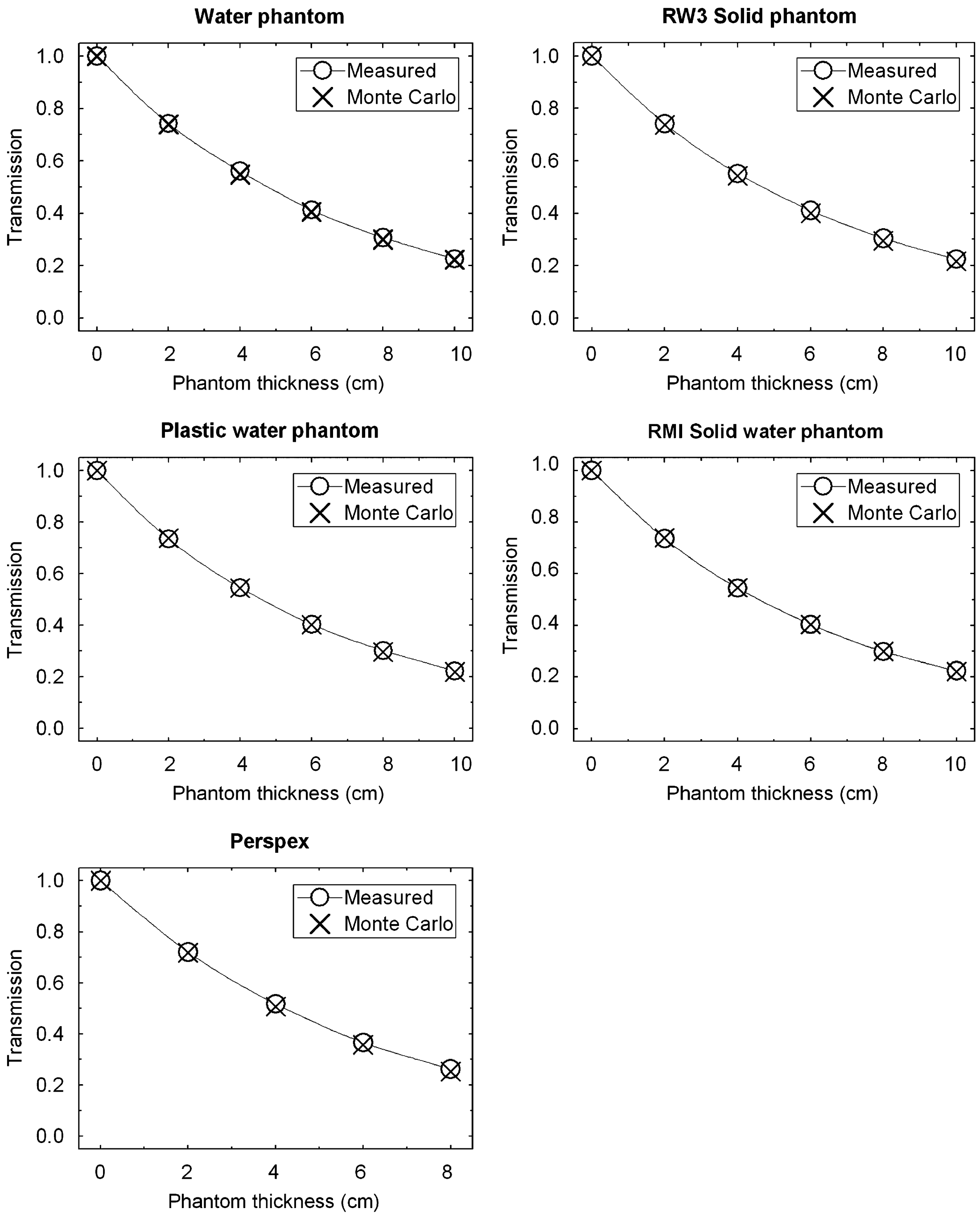

Fig. 3. A comparison of measured and EGSnrc calculated transmission values for technetium-99m gamma rays passing through varying thicknesses of five phantom materials. The phantom materials studied were water, RW3, Plastic Water, RMI 457 Solid Water and Perspex. The line passing through the measured data points have been applied for ease of reading the data and are not the actual data.

One aspect of the solid phantoms that will contribute to uncertainties in the transmission measurements is the inhomogeneity in the manufacture of the blocks, leading to variations in density (Allahverdi et al., 1999; Seuntjens et al., 2005). The results indicate that within the uncertainties, the Plastic Water, RMI-457 Solid Water and RW3 phantom materials meet the ICRU requirements for water equivalency at this particular energy.

The maximum uncertainty of the Monte Carlo calculations was less than 0.2%. The difference in transmission values between using the default and updated NIST cross-section data was less than 0.1% for all calculations. From this, the calculations that used NIST cross-section data are presented in this paper.

The Monte Carlo calculated and measured transmission values for the five phantom materials are presented in Fig. 3.

Table 2
Linear attenuation coefficients, μ (cm^{-1}), for the five phantoms studied determined using measured and Monte Carlo calculated transmission data and as calculated by the XCOM program for gamma rays emitted by a technetium-99m source

	Water	RMI-457	Plastic Water	RW3	Perspex
μ_{measured} (cm^{-1})	0.148	0.151	0.151	0.149	0.166
μ_{EGSnrc} (cm^{-1})	0.151	0.151	0.152	0.153	0.170
μ_{XCOM} (cm^{-1})	0.154	0.154	0.155	0.155	0.177

The line passing through the measured data points has been applied for ease of reading the data and is not the actual data. Each graph shows the Monte Carlo calculated and the measured transmission data as a function of phantom thickness. The agreement between the Monte Carlo and measured data is good with a maximum difference of 1.3%, but in most cases the deviation was less than 1%.

The linear attenuation coefficients based on the measurements, μ_{measured}, the EGSnrc calculated transmission values, as well as the coefficient calculated using XCOM, are presented in Table 2. The results are such that the Monte Carlo calculated linear attenuation coefficients agree with the measured values to within 2.4%, with the standard error of the coefficient being less than 0.7%. This level of agreement is acceptable due to the variations that we expect as detailed above.

The value of the linear attenuation coefficient derived from XCOM is greater than those derived from the measured and the EGSnrc calculated transmission data. For the solid phantoms, the linear attenuation coefficient μ was 2% greater than the Monte Carlo values, while for Perspex the coefficient was 4% greater. These results are consistent with Reniers et al. (2004) who found differences of 3% between EGSnrc (using updated cross-section data) and XCOM calculated attenuation coefficients. In comparison, the linear attenuation coefficients for water and Perspex as measured by Midgley (2005) are in good agreement with the XCOM calculated coefficients, but 3.3% and 5.4% greater, respectively, than the measured coefficients in this paper. It should be noted that Midgley used a different detector in his measurement of the gamma rays.

The differences between the measured and calculated linear attenuation coefficients are attributed to (a) the energy resolution of the inorganic scintillator crystal in the gamma-camera (±10% FWHM at 140 keV), (b) the partial energy deposition of the gamma rays creating background noise, (c) the Monte Carlo and XCOM calculated coefficients being based on the attenuation of a monoenergetic gamma source as compared to an actual spectrum, and (d) the lead collimator used to hold the radionuclide generating X-rays via fluorescence.

As mentioned in the introduction, the technetium-99m source emits gamma rays of other energies that may be within the energy window of the data acquisition system software. These are not included in either the Monte Carlo or XCOM calculations that are expected to introduce additional deviations as compared to the measured data.

4. Conclusion

In this project, transmission values of gamma rays have been used as a method of testing the water equivalence of four solid phantoms. To test the water equivalency of solid phantoms, we have used experimental and Monte Carlo methods with the criteria for water equivalence being based on ICRU recommendations.

The experimental data was measured by using a technetium-99m radionuclide source in conjunction with a nuclear gamma camera as the detector. The experimental results indicate that for the photon energy tested of 140.5 keV, the RMI457 Solid Water, CMNC Plastic Water and PTW RW3 had transmission values that were for most cases within 1.0% of those of water thus meeting the ICRU requirements for water equivalency. This means that these solid phantoms could be used for radiation dosimetry of photons at this energy. Perspex cannot be considered water equivalent for the photon energy tested. Verification of the experimental results by performing Monte Carlo calculations shows similar results with the level of agreement being within 1.3% after simulating the transport of gamma photons through the phantoms.

The agreement in linear attenuation coefficients calculated from the transmission values of the experimental and Monte Carlo values were within 2.4%, and greater disagreement with those determined from NIST data. An improvement in the Monte Carlo calculations could be achieved by modelling the lead container holding the radionuclide. In addition, determination of the actual spectrum of photons that reach the gamma camera could improve the agreement in the linear attenuation coefficients from the three methods used.

All solid phantoms that claim to be water equivalent should be checked in a similar manner before their use for dosimetry measurements. This is particularly important if one will use the solid phantom for photons with energies outside the range specified by the manufacturer. By using other radionuclides that emit lower energy gamma rays, further testing could be performed at lower photon energies where the photoelectric effect will become a more dominant interaction process. The experimental procedure could also be used as a quality assurance tool of the solid phantoms on a routine basis.

Acknowledgements

We would like to thank Dr. Dale Bailey from the Department of Nuclear Medicine, Royal North Shore Hospital, Sydney, Australia for allowing the use of equipment and providing the technetium-99m isotope.

References

Allahverdi, M., Nisbet, A., Thwaites, D.I., 1999. An evaluation of epoxy resin phantom materials for megavoltage photon dosimetry. Phys. Med. Biol. 44, 1125–1132.

Andreo, P., Burns, D.T., Hohlfield, K., Huq, M.S., Kanai, T., Laitano, F., Smyth, V., Vynckier, S., 2000. Absorbed dose determination in external beam radiotherapy, an international code of practice for dosimetry based on standards of absorbed dose to water. Technical Report Series No. 398, International Atomic Energy Agency, Vienna.

Badhwar, G.D., Robbins, D.E., Gibbons, F., Braby, L.A., 2002. Response of a tissue equivalent proportional counter to neutrons. Radiat. Meas. 35, 551–556.

Berger, M.J., Hubbell, J.H., Seltzer, S.M., Chang, J., Coursey, J.S., Sukumar, R., Zucker, D.S., 1998. XCOM: Photon Cross Sections Database. Available at ⟨http://physics.nist.gov/PhysRefData/Xcom/Text/XCOM.html⟩. National Institute of Standards and Technology, Physics Laboratory, Ionizing Radiation Division, Gaithersburg, MD, USA.

Brown, S., Bailey, D.L., Baldock, C., 2005. An investigation of the relationship between linear attenuation coefficients and CT Hounsfield units. Australas. Phys. Eng. Sci. Med. 29, 140.

Chu, S.Y.F., Ekstrom, L.P., Firestone, R.B., 1999. The Lund/LBNL nuclear data search. Available at ⟨http://nucleardata.nuclear.lu.se/nucleardata/toi/index.asp⟩. Lunds Universitet, Sweden.

Demir, B., Bilge, H., Dincbas, F.O., Koca, A., Karacam, S., Gunhan, B., 2005. The effect of pull back technique on dose distribution in the junction region for 90Sr/90Y intravascular brachytherapy sources. Radiat. Meas. 39, 29–32.

Healy, B.J., Gibbs, A., Murry, R.L., Prunster, J.E., Nitschke, K.N., 2005. Output factor measurements for a kilovoltage X-ray therapy unit. Australas. Phys. Eng. Sci. Med. 28, 115–121.

Hermann, K.P., Geworski, L., Muth, M., Harder, D., 1985. Polyethylene-based water-equivalent phantom material for X-ray dosimetry at tube voltages from 10 to 100 kV. Phys. Med. Biol. 30, 1195–1200.

Hill, R., Holloway, L., Baldock, C., 2005. A dosimetric evaluation of water equivalent phantoms for kilovoltage X-ray beams. Phys. Med. Biol. 50, 331–344.

ICRU, 1989. Tissue substitutes in radiation dosimetry and measurement. Report 44, International Commission on Radiation Units and Measurements, Bethesda, MD, USA.

Jaszczak, R.J., Greer, K.L., Floyd Jr., C.E., Harris, C.C., Coleman, R.E., 1984. Improved SPECT quantification using compensation for scattered photons. J. Nucl. Med. 25, 893–900.

Johns, H.E., Cunningham, J.R., 1983. The Physics of Radiology. Charles C. Thomas, Springfield, IL, 796pp.

Kawrakow, I., 2000. Accurate condensed history Monte Carlo simulation of electron transport. I. EGSnrc, the new EGS4 version. Med. Phys. 27, 485–498.

Liu, L., Prasad, S.C., Bassano, D.A., 2003. Evaluation of two water-equivalent phantom materials for output calibration of photon and electron beams. Med. Dosim. 28, 267–269.

Meigooni, A.S., Li, Z., Mishra, V., Williamson, J.F., 1994. A comparative study of dosimetric properties of Plastic Water and Solid Water in brachytherapy applications. Med. Phys. 21, 1983–1987.

Metcalfe, P., Kron, T., Hoban, P., 1997. The Physics of Radiotherapy X-rays from Linear Accelerators. Medical Physics Publishing, Madison, WI, 493pp.

Midgley, S.M., 2005. Measurements of the X-ray linear attenuation coefficient for low atomic number materials at energies 32–66 and 140 keV. Radiat. Phys. Chem. 72, 525–535.

Mitchell, G., Kron, T., Back, M., 1998. High dose behind inhomogeneities during medium-energy X-ray irradiation. Phys. Med. Biol. 43, 1343–1350.

Reniers, B., Verhaegen, F., Vynckier, S., 2004. The radial dose function of low-energy brachytherapy seeds in different solid phantoms: comparison between calculations with the EGSnrc and MCNP4C Monte Carlo codes and measurements. Phys. Med. Biol. 49, 1569–1582.

Rogers, D.W., Kawrakow, I., Seuntjens, J., Walters, B.R.B., Mainegra-Hing, E., 2000. NRCC Report PIRS-702. NRC user codes for EGSnrc. Ionizing Radiation Standards, National Research Council of Canada.

Seuntjens, J., Olivares, M., Evans, M., Podgorsak, E., 2005. Absorbed dose to water reference dosimetry using solid phantoms in the context of absorbed-dose protocols. Med. Phys. 32, 2945–2953.

Verhaegen, F., 2002. Evaluation of the EGSnrc Monte Carlo code for interface dosimetry near high-Z media exposed to kilovolt and ^{60}Co photons. Phys. Med. Biol. 47, 1691–1705.

Williams, J.R., Thwaites, D.I., 2000. Radiotherapy Physics in Practice. Oxford University Press, Oxford, 332pp.