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A measurement of absorbed dose to water per unit incident 7 MeV photon fluence

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Abstract. After isolating the effects due to 7 MeV photons, measurements were made of the ratio of the ^{60}Co exposure equivalent charge from a Baldwin–Farmer ion chamber in a water phantom, divided by the on-axis fluence of incident 7 MeV photons. This quantity is the ratio between the conversion factor from fluence to absorbed dose to water and the chamber calibration factor specified by various dosimetry protocols. The measured value is a test of the Monte Carlo codes and dosimetric theory used to derive these two factors. A value of 4.13×10^{-13} C kg^{-1} cm^2 ± 1.6% was measured. In order to assess the ion chamber charge due to scattered 7 MeV photons, a subsidiary experiment measured the dose due to scattered photons originating in a series of iron plates. Agreement was obtained between the measured dose as a function of iron plate thickness and that calculated using the EGS Monte Carlo simulation systems and also between the measured and calculated absorbed dose-depth curves. The results may be viewed as an experimental measurement, with 2-3% uncertainty, of the absorbed dose to water per unit incident 7 MeV photon fluence, or of the ion chamber calibration factor specified by dosimetry protocols.

1. Introduction

Dosimetry for high energy x-ray therapy beams from linear accelerators is routinely carried out with ion chambers which have been calibrated in terms of exposure using ^{60}Co photon beams. The technique for converting the ion chamber charge measured in a phantom to the absorbed dose to the phantom material is steadily evolving. Recently two major protocols have been established, one by the Nordic Association of Clinical Physicists (NACP 1980) and the other by the American Association of Physicists in Medicine (AAPM 1983). These are considerably different in approach from earlier protocols (ICRU 1969, HPA 1969, SCRAD 1971) and yield better results due to our improved understanding. There are, however, still overall uncertainties of about 3% in the dose estimates.

In both new protocols, a central role is played by the stopping power ratio averaged over the electron spectrum at the point of measurement. These values are computed using Monte Carlo calculations to determine the electron spectra. At the same time, the use of Monte Carlo calculations to calculate dose distributions is expanding rapidly.

These Monte Carlo calculations, as well as the various correction factors used in the protocols, are difficult to verify experimentally and the verifications inevitably

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depend on assumptions. The experiment described here was designed as a consistency check on the Monte Carlo calculations used to calculate depth–dose curves and stopping power ratios. Because of the experiment's unique nature, the types of assumptions introduced are different from those used in many other experimental checks and the result provides a stringent constraint for future calculations to satisfy.

In essence the experiment measured, for a nearly monoenergetic 7 MeV photon beam, the absorbed dose to water at 5 cm depth in a water phantom, (i) by using an exposure calibrated Baldwin–Farmer ion chamber and (ii) by measuring the 7 MeV photon fluence incident on-axis. Using the ion chamber the absorbed dose to water at 5 cm depth D_λ(Gy) was determined as

$$D_\lambda = Q_\lambda N_x F_\lambda \tag{1}$$

where Q_λ (C) is the ion chamber charge measured at 5 cm depth in the phantom and caused by incident photons of quality λ, N_x (C kg^{-1}C^{-1}) is the ^{60}Co exposure calibration factor and F_λ is a factor with dimensions J C^{-1} (Gy C^{-1} kg) which is derived using the various protocols. Using the measured 7 MeV photon fluence, the absorbed dose to water at 5 cm depth was determined as

$$D_\lambda = \Phi_\lambda K_\lambda \tag{2}$$

where Φ_λ(cm^{-2}) is the fluence of γ rays incident on-axis on the water phantom and K_λ (Gy cm^{-2}) is a conversion factor from incident on-axis fluence to absorbed dose to water at 5 cm depth obtained from Monte Carlo calculations (Rogers 1984a, see also § 2.2 below).

In order to separate measured and calculated quantities, it is useful to introduce the purely measured quantity S_7, the ^{60}Co exposure equivalent at 5 cm depth per unit incident 7 MeV γ ray fluence. S_7 (C kg^{-1} cm^2) is defined as

$$S_7 = Q_7 N_x / \Phi_7 \tag{3}$$

This experimentally measured value can then be compared to a calculated estimate which, by combining equations (1) and (2), is given by

$$S_7 = K_7 / F_7 \tag{4}$$

In practice Q_{tot}, the total charge from the ion chamber, is measured. This includes Q_c, the various charges caused by the contaminants in the 7 MeV beam (e.g. 197 keV γ rays, scattered phonons, etc), which must be subtracted to leave Q_7, the charge due solely to the 7 MeV beam, i.e.

$$S_7 = \left(Q_{\text{tot}} - \sum_c Q_c \right) N_x \Big/ \Phi_7 \tag{5}$$

where the summation is over all beam contaminants c. By combining equations (1) and (2), $Q_\lambda N_x = K_\lambda \Phi_\lambda / F_\lambda$ and substituting into equation (5) gives

$$S_7 = \frac{Q_{\text{tot}} N_x}{\Phi_7} - \sum_c \frac{K_c}{F_c} \frac{\Phi_c}{\Phi_7} \tag{6}$$

Equation (6) identifies the 'experimentally' measured quantity S_7 and contains correction terms to account for beam contamination. These involve K_c/F_c, the very ratio of calculated coefficients (albeit at the energies of the contaminants) that we wish to measure for the 7 MeV beam (equation 4). Since, however, the total correction term in equation (6) amounts to less than 10%, even relatively large uncertainties in K_c and

F_c values for the contaminants contribute only a very small uncertainty to the final value of S_7.

The remainder of this paper is devoted to describing the determination and verification of the quantities in equation (6) prior to the final evaluation of S_7 in § 5.6 and a comparison of the measured and calculated values in § 6. In the following section, we discuss how we obtained the values used in this work for F_λ, the exposure to absorbed dose conversion factors which are based on various dosimetry protocols, and for K_λ, the photon fluence to absorbed dose conversion factors which are based on our own Monte Carlo calculations. Both of these values are important since they enter into the correction term in equation (6) and because the final result of our measurement is a test of the ratio of their values at 7 MeV (as given in equation 4).

Section 3 gives a description of the 7 MeV source used for these measurements and presents the measured values of the relative fluence of the discrete contaminant photons in the 7 MeV beam (i.e. the Φ_c/Φ_7 values for discrete photons for use in equation 6). Section 4 describes the absolute measurement of Φ_7, the 7 MeV photon fluence at the face of the water phantom.

Section 5 deals with the ion chamber measurements and several auxiliary experiments done to verify some of the values used in equation (6). The ion chamber measurements are made very difficult by the weakness of the 7 MeV source which only creates a current of ≈ 70 fA in a Baldwin–Farmer ion chamber. Section 5.1 describes the electronics used to measure charge from the ion chamber in an accelerator environment while also measuring the photon fluence. Section 5.2 is concerned with the determination of N_x, the ion chamber exposure calibration factor used in equation (6). The next section describes a technique developed to minimise the uncertainties caused by the ion chamber's leakage current since the leakage current could represent a large fraction of the measured current if precautions were not taken. In § 5.4 the details of the determination of the relative fluence Φ_c/Φ_7 for scattered photons are given. In the final analysis, this correction for scattered photons was not a significant factor but our measurements provide a unique quantitative confirmation of the calculation of dose due to scattered photons. As a final check that we can properly take into account all the components in the beam, in § 5.5 we present a comparison of the calculated and measured depth–dose curves for our particular phantom.

2. Values of F_λ and K_λ

2.1. *The F_λ factor*

The factor F_λ defined in equation (1) is similar to the familiar C_λ. However, when using the newer dosimetry protocols (NACP 1980, AAPM 1983) this factor is no longer the simple constant originally called C_λ. Nonetheless it is useful to summarise the results of various protocols into a single number F_λ calculated for a particular ion chamber in a given geometry and beam quality. The units of rad R^{-1} will be used (multiply by 38.76 to convert to SI, i.e. Gy C^{-1} kg $=$ JC^{-1}).

Of special interest for this work is the value of F_λ evaluated for a Baldwin–Farmer chamber for the case of a nearly monoenergetic beam of 7 MeV photons incident on a water phantom. Dosimetry protocols do not cover monoenergetic γ ray beams. Therefore we have approximated our beam ($\bar{E} = 6.8$ MeV) with a 24 MV x-ray beam. This has been done for the purpose of determining F_λ because our estimates of the stopping power ratios for these two beams are the same and stopping power ratios are the main variable in the determination of F_λ. The stopping power ratios used were based on various calculations, primarily those of Nahum (1983). The value of F_λ is only slightly dependent on the actual value chosen for the equivalent x-ray beam, its value changing by less than 0.5% between 20 and 25 MV.

With the 24 MV approximation for the beam energy ICRU (1969) gives $F_7 = 0.90$ rad R^{-1}. The new AAPM protocol requires more parameters. AAPM determined a value of $F_7 = 0.927$ rad R^{-1} using the following parameters defined in the protocol (several of which depend on the specification of the ion chamber given in § 5.1): $N_{\mathrm{gas}}/N_{\mathrm{x}} = 8.506 \times 10^{-3}$ Gy R^{-1}, $\bar{W}/e = 33.7$ J C^{-1}, $P_{\mathrm{wall}} = 1.000$ (where $\alpha = 0.13$ for a 0.06 g cm^{-2} C wall), $(\bar{L}/\rho)^{\mathrm{water}}_{\mathrm{air}} = 1.095$ for 20–25 MeV x-rays, $P_{\mathrm{ion}} = 1.00$ and $P_{\mathrm{repl}} = 0.995$. In this calculation we have ignored the build-up cap although it was used for the in-phantom measurements (see below). Similarly a value of $F_7 = 0.926$ rad R^{-1} was calculated using the NACP (1980) protocol with the following parameters: $p_{\mathrm{u}} s_{\mathrm{w,air}} = 1.088$ for 20–25 MeV x-rays, $k_{\mathrm{att}} = 0.990$, $k_{\mathrm{m}} = 0.985$ (from Johansson *et al* 1977 for a carbon chamber with a PMMA cap; this is the only factor which is not taken directly from the protocols) and $\bar{W}/e = 33.85$ J C^{-1}. Note that there is a difference of 0.4% in the values used by the protocols for $\bar{W}/e$ (the NACP value being for dry air, the AAPM value for 50% humidity). Apart from k_{m} we have chosen to use the protocol values as specified, despite known errors such as double counting of β_{wall} in the AAPM protocol (Rogers *et al* 1984).

All of the ion chamber measurements reported here for the 7 MeV beam were done with a Baldwin–Farmer ion chamber with its PMMA build-up cap on (see § 5.1 for complete specifications). In retrospect this was an unfortunate choice. To estimate the size of the effect of the cap, T_λ was defined as follows

$$T_\lambda = \frac{Q_\lambda(\mathrm{off})}{Q_\lambda(\mathrm{on})} = \frac{F_\lambda(\mathrm{on})}{F_\lambda(\mathrm{off})}$$

where Q_λ is the charge measured with the build-up cap off or on, in beam quality λ for a given photon fluence. Kutcher *et al* (1977) measured T_λ for a variety of photon beams for a carbon walled Baldwin–Farmer ion chamber with a PMMA build-up cap. They found $T_{20} = 1.005 \pm 0.002$ for a 20 MeV x-ray beam. McEwan (1979) calculated T_λ for the same type of chamber and found $T_{20} = 1.002$, consistent with the experimental results. Since these values are uncertain but close to unity, we have ignored the effect of the build-up cap on calculated values of F_λ although it may have a +0.2–+0.5% effect.

In order to make ~10% corrections for photon contaminants in the beam values of F_λ were needed for 0.110–1.3 MeV γ rays. These values of F_λ were obtained by extrapolating the AAPM formalism to low energies and treating the chamber as thick walled (i.e. assuming the PMMA build-up cap was water equivalent). The values are given in table 1.

2.2. *Monte Carlo calculations and values of K_λ*

In this work we have used the results of Monte Carlo calculations for a variety of applications. Our primary requirement was for values of K_λ, the conversion factor from photon fluence to absorbed dose to water. These are needed at a variety of energies in order to calculate the contaminant correction factor in equation (6). More importantly, our final measured value of S_7 is a check of the ratio of the calculated values of K_7 to F_7 (equation 4). We have also used Monte Carlo simulations to determine the fraction of the dose in the water phantom due to knock-on electrons

Table 1. Summary of relative fluence measurements at the face of the water phantom for discrete γ ray components in the 7 MeV source spectrum.

γ ray energy (MeV)	Relative fluence Φ/Φ_7	Relative dose† at 5 cm depth (%)	K_λ (Gy cm^2)	F_λ (rad R^{-1})	Origin of radiation
0.110	0.133	0.5	6.12×10^{-13}	1.02	^{19}F(p, p′γ)^{19}F
0.197	0.440	2.9	1.09×10^{-12}	0.96	
0.511	0.157	2.4	2.50×10^{-12}	0.96	see text
1.24	0.022	0.7	4.90×10^{-12}		
1.35	0.031	1.1	5.22×10^{-12}	0.95	^{19}F(p, p′γ)^{19}F
1.46	0.008	0.3	5.55×10^{-12}		
	0.791	7.9			
6.13	0.266	24.6	1.39×10^{-11}		
6.92	0.345	35.0	1.52×10^{-11}	0.927	^{19}F(p, $\alpha\gamma$)^{16}O
7.12	0.389	40.3	1.55×10^{-11}		
	1.00	100	1.497×10^{-11}		

† These differ from the values in Rogers (1983) because they apply to the new target chamber and because more accurate K_λ factors have been used.

and scattered photons. This is needed for the subtraction of contaminants in equation (6). In § 5, we present quantitative comparisons between these calculations and measured values. A third requirement for Monte Carlo simulations concerned the efficiency of the NaI detectors used to monitor the photon fluence (see § 4).

The EGS (Electron-Gamma-Shower) system of computer codes for simulating the transport of electrons and photons using Monte Carlo techniques has been used for these calculations. The EGS system takes into account all the physical processes of importance for the energy region of interest. Details can be found in Ford and Nelson (1978) and Rogers (1982, 1984a, b). The EGS users code DOSE2 has been used to calculate K_λ, the conversion factor from absorbed dose to water per unit fluence incident on-axis with beam quality λ. For contaminant photons, where we only need approximate values for use in equation (6), the values of K_λ were taken from Rogers (1984a). The published values are for broad parallel incident beams. They were converted to values appropriate to a point source using a $1/r^2$ factor. For the 7 MeV photons, more detailed calculations were performed which took into account the finite dimensions of the water phantom used in the present experiments. The phantom was simulated by a cylinder, 8.3 cm in radius and 16 cm long with the point source 50 cm away on the cylinder's axis. The effect on the calculations of the finite size of the phantom compared to a semi-infinite slab was to reduce the absorbed dose per unit incident fluence by 2.7%. The values calculated are given in table 1 for a depth of 5 cm. The uncertainty in these values is caused almost entirely by uncertainty in the photon (Compton) cross-section, which in this energy region is between 1 and 2%. However, no experimental checks of these conversion factors are available.

A second EGS user code, CONVERT, has been used to calculate the dose from scattered photons and from knock-on electrons generated by 7 MeV photons passing through a plate of arbitrary material (Rogers 1983). For these calculations a point source was placed at various distances from the plate and collimated to a specified radius. The photon and particle spectra hitting a disc at an arbitrary distance from the plate were determined. By assuming all these particles were incident normal to the surface, the depth–dose curves for electrons and photons of arbitrary energy reported in Rogers (1984a) can be folded with the spectra to give the depth–dose curves in the phantom. Since calculations showed that between 50 and 100 cm the planar fluence of scattered photons obeyed a $1/r^2$ law, a $1/r^2$ correction was applied to the calculated depth–dose curve.

A third users code, JACKET, described in Rogers (1982) has been used to calculate the response functions of a 5 in ×4 in (12.7 cm × 10.16 cm) NaI detector. It was often necessary to know the efficiency of an arbitrary energy window and hence the entire response function was needed. The accuracy of this code for 6 MeV photons has been verified experimentally to within 2% (Mach and Rogers 1983).

3. The 7 MeV photon source

The NRCC 7 MeV photon source was originally developed to calibrate radiation protection instrumentation and has been described in detail previously (Rogers 1983). It consists of a 2.7 MeV beam of protons incident on a 6 mg cm^{-2} thick target of CaF_2. The ensuing $^{19}F(p, \alpha\gamma)^{16}O$ reaction produces a triplet of γ rays with energies of 6.13, 6.92 and 7.12 MeV which will be referred to throughout this paper as 7 MeV photons. For calibration of radiation protection instruments the fluence of these 7 MeV photons is measured using NaI and Ge(Li) spectrometers and the dose equivalent is deduced using calculated fluence to dose equivalent conversion factors (Rogers 1984a). Figure 1 shows the experimental set-up used for the experiments reported in § 5 and the final design of the target chamber.

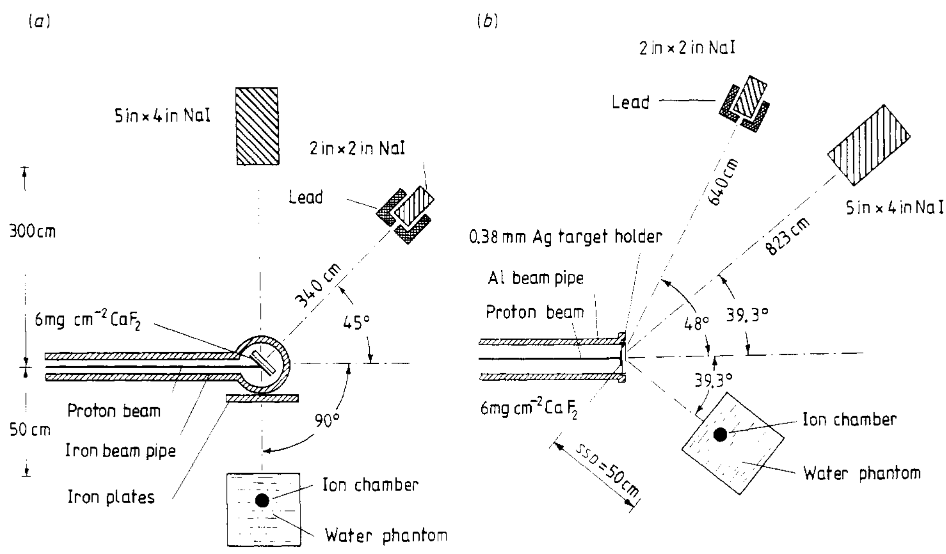

Figure 1. (*a*) Old target chamber and experimental set-up to measure the dose from photons scattered by iron plates. The target chamber had walls equivalent to 2.6 mm of iron and in addition had relatively large amounts of material above and below the target. (*b*) The new target arrangement with the CaF_2 deposited directly onto an 0.38 mm thick disc of silver at the end of an aluminium tube (22 mm in diameter, 0.8 mm thick). The silver was cooled by a stream of air. The Ag weighed ~1.5 g while the Al tube weighed ~1.5 g cm^{-1}.

Along with the 7 MeV photons of interest, a variety of contaminant radiations were present in the beam. Contaminant electrons and positrons are an inherent part of any high energy photon source since they are created by scattering of the photons by the target chamber and to a less extent by the air. The measurement of the absorbed dose to water from these electrons is reported in § 5.5.

The broad spectrum of photons scattered by the target chamber were also a beam contaminant. The new target chamber reduced their effect by a factor of three to 1% of the absorbed dose from the 7 MeV photons. Their measurement is discussed in § 5.4.

A third type of beam contamination was discrete γ rays. Although they represent about 8% of the absorbed dose from the beam, they are less of a problem since their fluence can be explicitly measured relative to the 7 MeV fluence using Ge(Li) spectrometers (see e.g. figure 5, Rogers 1983). Table 1 presents a summary of the fluence relative to that of the 7 MeV photons for each of the discrete lines in the spectrum measured at the location of the front face of the water phantom. These have been converted to relative dose measurements using the calculated conversion factors shown. The fluence measurements required knowledge of the measured relative efficiency curve for the Ge(Li) spectrometer used. This curve had been measured by Dixon (1981). It was further refined with the results of absolute calibrations using a ^{60}Co source ($\pm 1\%$ uncertainty) and the absolutely calibrated NRCC 6.13 MeV photon source ($\pm 2\%$ for a Ge(Li) detector, Mach and Rogers 1983). Considerable care was needed to extract the relative fluence of the low energy contaminants and the 7 MeV photons because of the Doppler broadening of the 6.92 and 7.12 MeV lines. The measurement was analysed twice; once based on the relative peak efficiencies and a second time based on the entire response function above 5 MeV as determined experimentally and from the Monte Carlo calculations. Both techniques yielded the same results.

The sources of the discrete γ ray background lines are well understood (table 1) except for the 511 keV peak which comes from several sources. With the new target chamber we estimate that for the 511 keV photons: (i) $\sim$54% came from the target area including those released from the e^+-e^- decay of the 6.05 MeV level in ^{16}O and those created by 7 MeV photon pair production events in the target chamber wall; (ii) $\sim$40% came from pair production events in the air and walls of the room; and (iii) $\leqslant$6% came from the Ge(Li) detector housing. This latter 6% does not contribute to the dose and the rest were treated as if they originated in the target chamber (this introduces negligible error for the assessment of dose at 5 cm depth).

Radiation from room background was accounted for by subtraction of the chamber's leakage current which included any contributions from this source.

4. The absolute fluence measurement

The fluence of 7 MeV photons incident on the front face of the water phantom during an accelerator run was determined using

$$\Phi_7 = N_{2\times 2}\frac{N_{5\times 4}}{N_{2\times 2}}\frac{1}{\varepsilon_{5\times 4}}\frac{1}{4\pi r^2}\,C_{\mathrm{at}} \tag{7}$$

where $N_{2\times 2}$ is the number of counts from the 2 in $\times$2 in (5.08 cm $\times$5.08 cm) NaI monitor in a particular energy window measured during the run, $N_{5\times 4}/N_{2\times 2}$ is the ratio of counts observed in a window in the 5 in $\times$4 in (12.70 cm $\times$10.16 cm) NaI window to those in the 2 in $\times$2 in NaI window; $\varepsilon_{5\times 4}$ is the number of counts in the 5 in $\times$4 in NaI window per 7 MeV photon per sr leaving the source in the direction of the detector $\times 4\pi$,

$1/4\pi r^2$ gives the fluence at a distance r from the source and C_{at} (= 1 − 0.0015) accounts for out-scattering in the air between the source and the phantom. The ratio $N_{5\times4}/N_{2\times2}$ was measured before and after each set of runs because of a long term drift in the efficiency of the 2 in × 2 in NaI monitor (≈0.4%). The collimator for the 2 in × 2 in NaI monitor was chosen so that this counter had an acceptable count rate during the high intensity runs.

The entire spectra were recorded for the NaI spectrometers so that internal energy calibrations could be used for each run in order to compensate for slight rate dependent gain shifts. Pulsers were fed into each spectrometer system to monitor dead-time losses and to ensure pulse pile-up was negligible. With these precautions the number of counts in the range of interest (4.0–7.6 MeV) could be measured with a statistical uncertainty of ~ ± 0.3% for each run. This reduced to an uncertainty of ~ ±0.1% in the final result due to the large number of independent runs.

The value of $\varepsilon_{5\times4}$ for 6.13 MeV γ rays was determined using the associated particle technique described by Mach and Rogers (1983). The associated particle target chamber was placed with the CaF_2 target in the same position as for the ion chamber measurements. A 1.1% correction for angular distribution effects was needed to account for the NaI spectrometer being at 39° to the proton beam. These calibration measurements were complicated by a 19% contribution to the 5 in × 4 in NaI count rate from cosmic radiation. This problem was minimised by averaging the results of 11 separate accelerator runs for a total of 28 h of beam time with background measurements between runs.

These measurements could also be used to determine the absolute efficiency of the 5 in × 4 in NaI for 6.13 MeV photons by calculating the attenuation by the 823 cm of air (2.4%). The efficiency value so determined (±1%) was 1.5% lower than the value calculated for this geometry using the Monte Carlo code JACKET (uncertainty ±2%, Rogers 1982). This slightly lower measured value is in agreement with the results obtained for other geometries in which measurements were easier to make (Mach and Rogers 1983).

The measurements with the associated particle apparatus were for a 6.13 MeV beam. To take into account the composition of the 7 MeV photon beam and some minor Doppler shift effects, calculated response functions for the 5 in × 4 in NaI spectrometer were used along with the known intensity ratios for the 7 MeV photon source. These considerations led to a 5.0% decrease in the photon fluence at the water phantom per count in the energy window in the NaI spectrometer.

5. Ion chamber measurements

5.1. The ion chamber and associated electronics

The ion chamber used in these measurements was a Nuclear Enterprises model 2505/3 0.6 cm^3 Baldwin–Farmer chamber. It is 25 mm long with an outside diameter of 7.0 mm. It has 0.36 mm thick walls of pure carbon, a 1 mm diameter central electrode made of aluminium and a PMMA build-up cap with 4.6 mm walls and an outside diameter of 16.35 mm. The chamber was connected by a 10 m triaxial cable to a Keithley 602 electrometer whose output was either read by a digital voltmeter or fed to a nuclear electronics set-up which turned the analysers associated with the NaI spectrometers on and off at predetermined charge settings. These settings were calibrated against the Keithley output voltage for each series of measurements and were found to be stable within 0.05% over a period of several months. Charge measurements made using this technique agreed within 0.1% with timed measurements in the ^{60}Co beam.

5.2. ^{60}Co calibrations

The ion chamber in its PMMA build-up cap and associated electronics were calibrated using the Canadian primary ^{60}Co exposure standard for which the exposure rate is known to ±0.4% (1σ, Henry 1981). The exposure calibration factor of 1.195×10^6 kg^{-1} was reproduced six months later to within 0.16% after corrections for leakage current (0.06%) and standard air pressure and temperature corrections (~1.3%) were made. Humidity corrections and effects caused by volume and initial recombination (estimated at ~0.1%) were ignored.

Due to the difference of three orders of magnitude in strengths for the 7 MeV and ^{60}Co sources, two different charge measurement ranges were used on the electrometer, each with different calibration factors. By placing a lead block in front of the ion chamber in the ^{60}Co beam, an exposure rate was obtained for which both ranges could be used. A correction factor of 1.033 for the difference between the calibration factors on the two ranges was determined and was incorporated into the exposure calibration factor which was determined on the less sensitive range. This correction factor remained constant within ±0.5% over a six month period.

Based on carbon calorimeter measurements, the NRCC ^{60}Co unit has also been calibrated in terms of absorbed dose to water at 5 cm depth at an SSD of ~1 m to an accuracy of ±1% (1σ, Henry 1981). The Baldwin–Farmer chamber was calibrated in the same geometry. Both the AAPM and NACP protocols, using the value of k_m determined by Johansson *et al* (1977), give $F_{^{60}\mathrm{Co}} = 0.950$ rad R^{-1}. Using this value to deduce an absorbed dose calibration factor from N_x gives a value 1% higher than the value measured directly. This is well within the uncertainties involved. The exposure based calibration factor is used throughout this paper.

To test for effects of the PMMA build-up cap, measurements were done with and without it at 5 cm depth of water in the ^{60}Co beam. The calibration factors were the same to within 0.1%.

As a further check, ^{60}Co depth–dose curves in a water phantom were measured for an SSD of 1 m. Between depths of 1.5 and 9.0 cm, the results were 0.6 to 1% lower than the results tabulated by Johns and Cunningham (1969) when normalised by the exposure calibration.

The water phantom used was 16 cm wide, 16 cm thick and 30 cm high. The beam passed through the side walls which were 5 mm thick PMMA. The position of the ion chamber in the phantom was determined with an accuracy of ±0.3 mm and is given relative to the front face of the PMMA. The ion chamber volume was ≈5 cm below the upper surface of the water.

5.3. Leakage current subtraction

The low dose rates in the 7 MeV photon beam required efforts to be made to minimise the effects of the leakage current. A bias of −217 V was applied to the ion chamber during all the measurements. Tests in the high intensity ^{60}Co beam indicated that the collected charges differed by less than ~0.1% when opposite biases were applied. However, the fluctuations in the leakage current caused by changes in the applied bias would be intolerable in the measurements with the much less intense 7 MeV source.

Even after considerable precautions the largest source of uncertainty in the ionometric measurements with the 7 MeV photon source was the fluctuation in the leakage current i_L. The fluctuation was found to be proportional to the magnitude of i_L. The following method was used to reduce the leakage current and hence the uncertainty caused by its fluctuations.

A bias of -360 V was applied overnight and changed to -217 V prior to the measurements. The leakage current immediately reached about -50 fA and changed, at first rapidly, through negative values to zero and then slowly through positive values to the normal saturation level of about 10–15 fA. During this cycle there was a 4 h period when $i_L \leq 5$ fA and measurements were done. This pattern was tested repeatedly to assure that it was reproducible, and that the magnitude and polarity of i_L did not affect the in-beam reading. The second point was checked using the cobalt beam with a block of lead shielding the ion chamber. This reduced the ion chamber current to ≈ 130 fA. The voltage cycle described above was repeated a few times and although i_L changed each time between -15 and $+10$ fA throughout the cycle, the extreme values of the net ^{60}Co charge measurements were within 0.7 fA of their average value, indicating no dependence on the leakage current to within $\pm 0.3\%$ under run conditions. The overall uncertainty in the measured current includes this uncertainty plus statistical uncertainty due to fluctuations in i_L and in measuring the charge.

5.4. Determination of scattered photon contribution

The dose at the calibration point from 7 MeV photons scattered by the target chamber and target backing is potentially significant but difficult to assess because of its continuous nature. Experiments were done with the old and the new target chambers. One experiment with the old chamber will be described in some detail since it confirms the accuracy of the Monte Carlo calculations which were also applied to the new chamber situation.

The experiment consisted of measuring the ion chamber charge per unit 7 MeV photon fluence incident on the water phantom placed at an SSD of 50 cm as a series of rectangular 16 cm $\times$ 23 cm iron plates, 0.26 cm thick, were placed in line with the water phantom next to the target chamber (see figure 1*a*). The wall of the target chamber was equivalent in thickness to one iron plate. The 2 in $\times$ 2 in NaI monitor was not shielded by these plates. Separate calibration runs were done with a Ge(Li) detector in place of the water phantom for each number of plates in order to determine the fluence of attenuated 7 MeV and discrete contaminant γ rays per 2 in $\times$ 2 in monitor count. The ion chamber measurements were done at a depth of 5 cm in the water phantom to ensure electron contamination was eliminated. Leakage current was monitored as described above and was the main contributor to the uncertainty of each measurement. The overall uncertainty on the final relative values of charge per unit fluence of 7 MeV photons incident on the water phantom was $\pm 0.6\%$ based on five series of measurements done at various times. These values are shown in figure 2 where they have been arbitrarily normalised to the value calculated with the Monte Carlo code CONVERT for the bare chamber which was taken to be equivalent to a single plate. The calculated absorbed dose to water at 5 cm depth per unit incident fluence of 7 MeV photons is shown with and without the contribution of scattered photons included. The values without the scattered component decrease because the contaminant discrete γ rays are attenuated by the additional iron plates more than the 7 MeV γ rays.

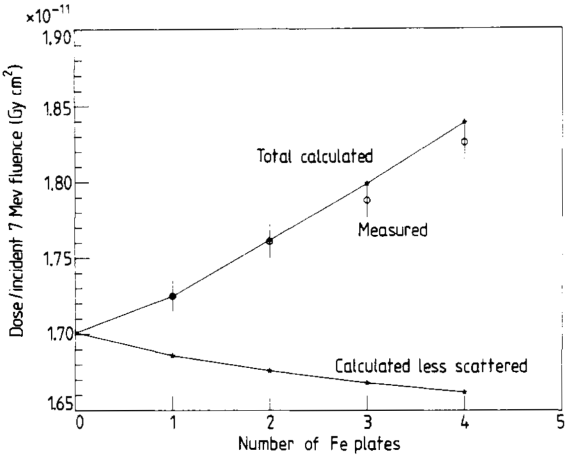

Figure 2. The absorbed dose to water at 5 cm depth per unit 7 MeV photon fluence incident on the water phantom as a series of 2.6 mm Fe plates was added in front of the old target chamber. The chamber alone had walls equivalent to 2.6 mm of Fe. The experimental results are normalised to the calculated results by setting the chamber results with no plates present equal to those calculated for a 2.6 mm plate of Fe although the geometries are not strictly comparable. The number of plates refers to the number in the calculation.

The good agreement between the measured change in ion chamber current per unit incident 7 MeV photon fluence and the calculated change in the absorbed dose to water at 5 cm depth per unit incident 7 MeV photon fluence gives confidence in our ability to assess the contribution due to scattered photons. For a 10.4 mm iron shield this amounts to 11% of the dose and for a 2.6 mm plate, which corresponds to the thickness of the chamber wall, the calculated scatter from a flat plate contributes 2.5% of the dose. Caution must, however, be taken in using these results to estimate the scattered dose from the old target chamber's cylindrical walls since the calculation only handles flat plates.

The new target chamber reduces the scatter problem, both because it reduces the chamber mass considerably and because the 7 MeV photons are primarily scattered by the flat silver backing. This backing is represented more accurately than the cylindrical walls of the old chamber by the source-next-to-plate geometry available in the Monte Carlo code. Calculations were done for a point isotropic source very close to a disc of silver 1 cm in radius, 0.38 mm thick. The calculated scattered photon absorbed dose to water at 5 cm depth for an SSD of 50 cm and an angle of 39° was 0.78% of the 7 MeV photon dose.

This scattered component was also measured by placing two additional silver target backings immediately behind the target and measuring the increase in ion chamber current per unit incident 7 MeV photon fluence at the phantom surface. A value of the scattered to unscattered dose fraction of $0.7 \pm 0.2\%$ was deduced for the target chamber on the assumption that attenuation of the discrete contaminant lines was negligible and that the scattered dose was proportional to the plate thickness as shown above for the iron plates. In view of the good agreement obtained for the calculations and the more detailed measurements made with the old target chamber, the calculated value of 0.78% was used in further analysis.

5.5. Depth–dose curves

On two separate occasions depth–dose curves were measured in the experimental set up of figure 1(*b*) with the water phantom at an SSD of 50 cm. The major source of relative uncertainty was the fluctuations in the leakage current which led to ±0.5–1% uncertainty. The values of ion chamber charge per unit incident 7 MeV photon fluence could be converted into absorbed dose to water per unit incident 7 MeV photon fluence by making use of the chamber's ^{60}Co exposure calibration factor and an average F_λ factor which would be depth dependent and would require knowledge of the relative intensities of all components of the incident electron and photon spectra. This detailed evaluation will be undertaken in the next section for a single depth, but for the purposes of this section, a single conversion factor will be defined by normalising to the theoretical result at 5 cm depth. The theoretical results for the absorbed dose to water per unit incident 7 MeV photon fluence were obtained using the Monte Carlo code CONVERT except for the 7 MeV photons where the explicitly calculated depth–dose curves were used.

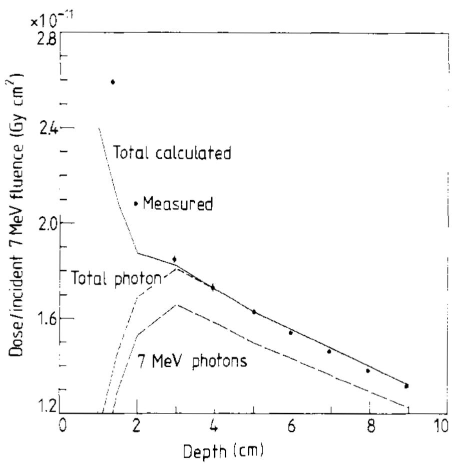

Figure 3. A comparison of the measured absorbed dose versus depth in the phantom and that calculated with EGS. The ion chamber calibration factor was assumed to be depth independent and normalised to give agreement at 5 cm depth. The total photon curve includes the absorbed dose from scattered and discrete contaminant photons and the remainder of the absorbed dose at shallow depths is due to knock-on electrons from the target backing. The agreement is impressive except at very shallow depths where certain electron contributions have been ignored in the calculations.

The good agreement past 3 cm depth between the measured and calculated total depth–dose curves shown in figure 3 is strong evidence of our ability to sort out the various components of the dose. At depths less than 2 cm, most of the dose is due to incident electrons. The calculated absorbed dose to water is lower than the measured absorbed dose to water in this region. This is not surprising since electrons from interactions in the air, which represent 14% of the mass between the photon source and the phantom, are ignored in the calculations as are other potential sources such as electrons knocked-on by the discrete γ ray contaminants.

An overly detailed comparison of the measurements and calculations must not be made because of the depth independent ion chamber charge to absorbed dose to water conversion factor used. However, the overall agreement is highly satisfactory.

5.6. *Measurements at a depth of 5 cm*

We are now in a position to use equation (6) to deduce S_7. At 5 cm depth, contaminant electrons are negligible. The measured relative fluence values Φ_c/Φ_7 for the discrete contaminants are given in table 1 with a one standard deviation uncertainty of $\leqslant \pm 5\%$. The values of K_c and F_c are also given there with an uncertainty of $\leqslant \pm 3\%$ each. For the scattered photon contaminants, the values of Φ_c/Φ_7 were taken from the Monte Carlo calculations with CONVERT which were verified in § 5.4. Because the correction term in equation (6) is $\leqslant 9\%$ of the total, the uncertainty in S_7 from these factors is $\leqslant 0.6\%$.

The final value of S_7, incorporating 36 measurements taken on six separate occasions, is 4.13×10^{-13} C kg^{-1} cm^2 (1.60×10^{-9} R cm^2) $\pm 1.6\%$. Table 2 summarises the sources of uncertainty.

Table 2. Sources and magnitudes of uncertainty in the measurement of S_7.

Source of uncertainty	1σ estimate (%)		Section where discussed
Absolute fluence measurement Φ_7		1.1	4
$N_{5\times4}/N_{2\times2}$	0.2		4
$\varepsilon_{5\times4}$	1.0		4
Distance effects	0.3		4
$N_{2\times2}$	0.1		4
Ion chamber charge measurement Q_{tot}		0.5	5.3
^{60}Co exposure calibration factor N_x		0.8	5.1, 5.2
Contaminant subtraction		0.61	5.6
Φ_c/Φ_7	0.45		3, 5.4
K_c	0.27		2.2, 5.6
F_c	0.27		2.1, 5.6
		1.6	

6. Discussion

A theoretical estimate of S_7 is given by K_7/F_7. The evaluation of both K_7 and F_7 requires detailed Monte Carlo calculations. This measured value of S_7 provides a self-consistency check on any Monte Carlo code which calculates these factors although there is some additional uncertainty introduced into the comparison by the correction factors required to deduce F_λ once the spectrum averaged electron stopping powers are calculated using the Monte Carlo code.

At present a rigorous comparison is not available since the same code has not been used to calculate both factors. However, from table 1 the factor K_7 has been calculated for the current situation to be 1.497×10^{-11}Gy cm^2.

If we use the F_7 values discussed in § 2, then we can deduce the S_7 values as shown in the first row of table 3. Only the value S_7 derived using the ICRU value for F_7 is outside the measurement uncertainties.

The measured value of S_7 can also be considered in other ways, depending on one's primary focus. One could look at it as the first measurement of absorbed dose to water per unit incident photon fluence and use it to check the various Monte Carlo calculations of K_7. The K_7 conversion factors deduced from the measured value of S_7 and the values of F_7 given by the various protocols are given in row three of table 3.

Table 3. Various interpretations and comparisons of the current results. The first row compares our measured value of S_7 with those deduced from our computed values of K_7 and the values of $\bar{F}_7$ deduced from the protocols. The second row compares the value of F_7 deduced from our measured value of S_7 and computed value of K_7 with those from the protocols. The third row compares our computed value of K_7 to the values derived from our measurement of S_7 and the values of F_7 deduced from the protocols.

		Protocol for F_λ		
Quantity evaluated	Present value	ICRU	AAMP	NACP
S_7 ($\mathrm{C\ kg^{-1}\ cm^2}$)	$4.13\times10^{-13}\pm1.6\%$	4.29×10^{-13}	4.17×10^{-13}	4.17×10^{-13}
F_7 ($\mathrm{rad\ R^{-1}}$)	$0.935\pm2.6\%$ (†)	0.90	0.927	0.926
K_7 ($\mathrm{Gy\ cm^2}$)	1.497×10^{-11}(‡)	1.44×10^{-11}	1.48×10^{-11}	1.48×10^{-11}

† For $\mathrm{J\ C^{-1}}$ multiply by 38.76. Note that no correction for the build-up cap has been used although it may increase F_7 by 0.2-0.5%.
‡ Statistical uncertainty 1%.

Detailed comparison to other calculated conversion factors is difficult because the comparison is geometry specific. One can note that Rogers (1984a) has shown that the 6 and 7 MeV photon conversion factors calculated with EGS for broad parallel beams are 3-7% lower than those calculated with other Monte Carlo codes. Since the present experimental result is slightly lower than the calculated EGS value, it can be concluded that the EGS result is in better agreement with experiment than the other calculations.

However, the current uncertainty in F_7 values is $\approx\pm3\%$ so that using these measurements as a check of fluence to dose conversion factors is of rather marginal value. On the contrary, if one accepts that the K_7 conversion factors calculated with EGS are accurate to ±2% then one can estimate $F_7 = K_7/S_7 = 0.935\ \mathrm{rad\ R^{-1}}\ \pm2.6\%$. This value is compared in table 3 with the values from various protocols which were discussed in the introduction.

7. Conclusions

The measurements reported here are unique by virtue of measuring an ion chamber's response in terms of the incident fluence of photons. Unfortunately, the measurements cannot be used on their own to distinguish between various calculations of fluence to absorbed dose to water conversion factors or of ion chamber exposure to absorbed dose conversion factors. Since both these calculated factors ultimately depend on detailed Monte Carlo calculations of radiation transport in a water phantom, the measured value of S_7 is best thought of as a constraint which should be satisfied by any attempt to calculate ion chamber exposure to absorbed dose conversion factors.

The detailed quantitative agreement shown in figure 2 between measured and calculated contributions to the absorbed dose due to photons scattered by plates of iron is good evidence of the EGS Monte Carlo code's ability to accurately predict the scattered photon component of the dose which can be very important in practical therapy beams.

Similarly the detailed quantitative agreement shown in figure 3 between the measured and calculated depth–dose curves in a phantom, includng the electron contaminant component, gives good evidence of our ability to calculate these various components of the dose in a therapy beam.

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Résumé

Mesure du rapport de la dose absorbée dans l'eau à la fluence des photons incidents pour une énergie de 7 MeV.

Après avoir sélectionné les effets dus aux photons de 7 MeV, les auteurs ont mesuré le rapport de l'exposition, calculée pour un faisceau de photons de Cobalt-60 à partir de la charge mesurée dans une chambre Baldwin-Farmer dans un fantôme d'eau, à la fluence sur l'axe de photons incidents de 7 MeV. Cette quantité représente le rapport du facteur de conversion de la fluence en la dose absorbée dans l'eau au facteur d'étalonnage utilisé dans divers protocoles de dosimétrie. La valeur mesurée constitue un test pour les programmes de Monte Carlo et la théorie utilisée pour déterminer ces deux facteurs. Cette valeur est $4{,}13\times10^{-13}$ C kg^{-1} $cm^2\pm1{,}6\%$. Afin d'estimer la charge produite dans la chambre par les photons diffusés de 7 MeV, les auteurs ont effectué une mesure de dose complémentaire tenant compte des photons diffusés provenant d'une série de plaques de fer. Un bon accord a été obtenu entre la dose mesurée pour différentes épaisseurs des plaques de fer et la dose calculée à l'aide du système EGS par la méthode de simulation de Monte Carlo; il en est de même pour les courbes de rendement en profondeur mesurées et calculées. Les résultats peuvent être interprétés comme une détermination expérimentale, comportant une incertitude de 2-3%, de la dose absorbée dans l'eau correspondant à une unité de fluence de photons incidents de 7 MeV, ou du facteur d'étalonnage de la chambre utilisée dans les protocoles de dosimétrie.

Zusammenfassung

Messung der Energiedosis in Wasser pro Einheit der Fluenz auftreffender 7 MeV-Photonen.

Nachdem die Effekte, die durch 7 MeV-Photonen entstehen isoliert worden waren, wurden Messungen des Verhältnisses der zur Co-60-Bestrahlung äquivalenten Ladung einer Baldwin-Farmer-Ionisationskammer in einem Wasserphantom und der Fluenz auftreffender 7 MeV-Photonen durchgeführt. Diese Größe ist das Verhältnis zwischen dem Konversionsfaktor von Fluenz zu Energiedosis in Wasser und dem Kammerkalibrierungsfaktor, der durch verschiedene Dosimetrie-Protokolle bestimmt wird. Der gemessene Wert dient der Überprüfung der Monte Carlo-Programme und der dosimetrischen Theorie, die zur Ableitung der beiden Faktoren benutzt wurden. Ein Wert von 4.13×10^{-13} C kg^{-1} $cm^2\pm1.6\%$ wurde gemessen. Um die Kammerladung, die durch gestreute 7 MeV-Photonen entsteht zu bestimmen, wurde ein zusätzliches Experiment durchgeführt. Dabei wurde die Dosis gemessen, die dadurch entsteht, daß Photonen an verschiedenen Eisenplatten gestreut werden. Übereinstimmung wurde erzielt zwischen der gemessenen Dosis als Funktion der Dicke der Eisenplatten und der mit Hilfe einer EGS-Monte Carlo-Simulation berechneten Dosis. Auch die gemessenen und berechneten Tiefendosiskurven stimmten überein. Die Ergebnisse können einesteils angesehen werden als Messungen der Energiedosis in Wasser pro Einheit der Fluenz auftreffender 7 MeV-Photonen oder andererseits als Messung des Ionisationskammer-Kalibrierungsfaktors, der durch Dosimetrie-Protokolle bestimmt wird.

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