Calculation of the Response of a NE2561 Ion Chamber in a Water Phantom for High Energy Photons

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Abstract. Absorbed dose to water calibrations of NE Technology Type 2561 chambers are carried out at the National Physical Laboratory (NPL) in both X-radiation from 4 - 19 MV and in ^{60}Co γ-radiation. Secondary standard ion chambers are calibrated against the primary standard graphite calorimeter by inserting these chambers at reference depths in a water phantom. The first part of this report describes the work which was undertaken in an attempt to reproduce the measured absorbed dose calibration factors for a secondary standard NE2561 ion chamber for a range of NPL photon qualities under standard calibration conditions. This calculated data did not reproduce the observed variation in calibration factor with beam filtration in the measured results. However, had this data been reproducible, in particular at 4 and 6 MV, then the possible causes of the observed variation in the measured results such as effects on the calibration due to chamber components would have been investigated. By comparing calibration factors and depth dose curves for NPL X-ray beams with a simulated clinical quality the practical impact on clinical dosimetry of these observed differences will be looked at.

The majority of this work was carried out using Monte Carlo techniques based on the EGS4 code system. The simulations were validated in several ways. Firstly, comparisons of calculated and measured depth dose curves in water were made at energies from 4 - 19 MV and in ^{60}Co γ-radiation. Then, data calculated with codes used in this work was compared with data produced by more well tested and well-established codes. The final validation method involved calculating the air kerma calibration factor of a NE2561 ion chamber in 2 MV X-rays and then comparing the calculated ratio of 2 MV air kerma calibration factor to ^{60}Co absorbed dose calibration factor with the measured value.

The calculated normalised absorbed dose to water calibrations were found to agree with measured values of k_Q, the ratio of absorbed dose calibration in quality Q to that in ^{60}Co, to within 1.0% (which corresponds to 2σ in the total uncertainty). The observed discrepancies were primarily random in nature. However, it was not possible to distinguish between the results for light and heavy filtration. This could have been due to large uncertainties on the calculated absorbed dose to water calibrations or to an undetected problem in the calculations or measurements. It was therefore not possible at this stage to investigate the observed change in calibration factor with beam filtration. The calculated calibration factor for a 6 MV X-ray beam from a Varian 2100C does, however, lie close to the NPL curve for heavily filtered beams (with a $TPR_{20/10}$ and depth dose curve similar to that of a NPL 6 MV (H) photon quality). The calculated and measured ratio of 2 MV air kerma calibration factor to ^{60}Co absorbed dose calibration factor agreed within 0.66% (which corresponds to less than 2σ in the total random uncertainty).

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1. Introduction

The National Physical Laboratory (NPL) provides a high-energy absorbed dose service, based on a primary standard graphite calorimeter, for the calibration of hospital secondary standard dosemeters at depth in a water phantom, such as the NE2561 ion chamber, in terms of absorbed dose to water[1]. The calibrations are performed in high energy X-radiation over the energy range 4 - 19 MV and in ^{60}Co γ-radiation. The latter quality was introduced to allow intercomparisons with the Bureau Internationale des Poids et Mesures (BIPM) and the other national standardising laboratories which have also developed absorbed dose standards in ^{60}Co γ-radiation.

Absorbed dose measurements with secondary standard and working standard ionisation chambers are carried out by inserting the chambers at reference depths in either a water or graphite phantom. The aim of the calculations presented here is to first reproduce the measured absorbed dose calibration factors for a secondary standard NE2561 ion chamber for a range of NPL photon qualities under standard calibration conditions at depth in a water phantom. If the data is reproducible, in particular at 4 and 6 MV, then the intention of this work is to also investigate the possible causes of the observed variation in calibration factor with beam filtration in the measured results. These energies are of most interest when looking at differences in the calibration curve with filtration, as it is flatter at lower energies causing less variation in the calibration factor with Tissue Phantom Ratio 20/10 ($TPR_{20/10}$). [$TPR_{20/10}$ is defined as the ratio of absorbed dose on the beam axis at 20 cm and 10 cm depths in a large water phantom for a fixed focal distance to the point of measurement with a 10 cm x 10 cm field.] This means that any uncertainty in the spectrum, which will correspond to an uncertainty in the $TPR_{20/10}$, will be of less significance at lower energies so that any effects caused by uncertainties in

the calculated spectrum of the NPL beam will be minimised.

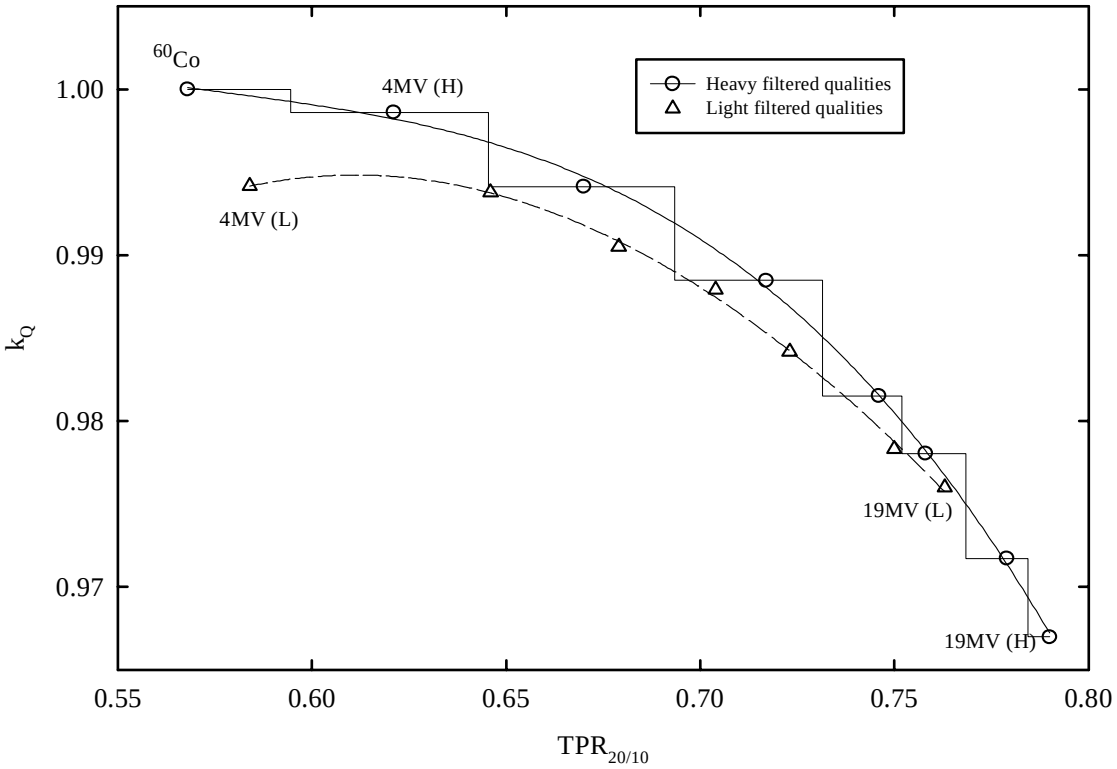

Figure 1: A Plot of Measured k_Q values versus $TPR_{20/10}$

Figure 1 shows a plot of k_Q, the ratio of absorbed dose calibration factor, N_w, in quality Q to that in ^{60}Co, versus $TPR_{20/10}$. It can be seen that there is between a 0.6% increase in k_Q at 4 MV up to a 0.8% decrease in k_Q at 19 MV when increasing the filtration in the NPL beam from light to heavy. It has been shown that the change in k_Q with filtration as a function of $TPR_{20/10}$ in the NPL beam is not related to a coincident change in the stopping power ratio[2]. Therefore the differences observed in the absorbed dose calibration factor, k_Q, for light and heavy filtered qualities may be due, in part, to the chamber construction and so, if possible, any effects due to chamber construction will be investigated. Clinical LINACs have varying amounts of beam filtration therefore for a given $TPR_{20/10}$, the amount of beam filtration can affect N_w for a chamber. The practical impact on clinical dosimetry will also be looked at by comparing calibration factors and depth dose curves for NPL X-ray beams with those for a simulated clinical quality.

The majority of these calculations were carried out using Monte Carlo techniques based on the EGS4[(i)] code system. One other purpose of this work was to improve these techniques for calculating the response of small, air filled ionisation chambers at depth in a phantom. This approach has also been used in calculating the response of a NE2561 chamber in a water phantom for medium energy photons in the energy range 130 - 280 kV[3].

Section 2 of this report along with Appendices 1 and 2 describes the EGS4 user-codes used in the simulation of a NE2561 ion chamber in a phantom, and their validation. The codes were validated by comparing calculated and measured results and/or by comparing results for the response of a cavity

[(i)] Electron - Gamma Shower version 4

chamber calculated using these new EGS4 user-codes with results calculated by other well-established and well validated user-codes. The calculation of the absorbed dose calibration factors for the NE2561 ion chamber inserted in a water phantom is covered in Section 3 of this report. Calculations are made for 4 and 6 MV X-radiation with light filtration (L) and between 4 - 19 MV X-radiation with heavy filtration (H) and for ^{60}Co γ-radiation and also for a typical clinical quality of 6 MV X-rays from a Varian 2100C clinical linear accelerator. The derived absorbed dose calibration factors are then compared with measured values of k_Q for NPL X-ray beams. The practical impact on clinical dosimetry will be investigated by comparing calculated depth dose curves and calculated N_w values for NPL and clinical qualities. Methods used to verify these calculations are also discussed.

2. EGS4 & Associated User-Codes

2.1 The EGS4 Code System

All of the calculations described in this report were carried out using the EGS4 code system with the PRESTA[(ii)] electron transport algorithm[4]. These codes form a general-purpose package for the Monte Carlo simulation of the coupled transport of electrons and photons in an arbitrary geometry for particles with energies ranging from a few keV to several TeV. The package, used in conjunction with a user-written code, calculates the development of an electron-photon cascade from a single incident electron or photon, and transports each particle through the geometry until it reaches a predefined energy cut-off or discard boundary. Electron-photon transport can be simulated in any of 100 elements or mixture of these elements, or any compound. The associated package PEGS4[(iii)], documented by Nelson et al[5], is used to generate data sets of the required materials for subsequent use by EGS4.

2.2 Description of User-Codes & Associated Programs

This section describes the four EGS4 user-codes used in this work. MOBALTRN and NPLLINAC are user-codes that calculate phase space spectra from the NPL radiation facilities under standard therapy level calibration conditions. These phase space spectra are then used as input by the user-code PHSCHAM to calculate the full phase space information on the surface of a stemless thimble chamber in a phantom. DOSCHAM can use either the phase space information generated by NPLLINAC, MOBALTRN or PHSCHAM as input in order to calculate the dose deposited in a stemless thimble chamber. All of the codes have been developed at the NPL and are at present prototype versions for NPLEGS[(iv)]. Also described in this section is the FORTRAN program DRATIO which has been used in the analysis of the calculated results.

The EGS4 user-code MOBALTRN (NPLEGS Prototype Version 1.00) simulates the passage of photons through the NPL ^{60}Co Mobaltron unit and collimation system in order to calculate the ^{60}Co phase space spectrum (see Figure 2). Similarly the EGS4 user-code NPLLINAC (NPLEGS Prototype Version 1.00) simulates the passage of electrons and photons through the X-ray production, collimation and filtering configuration in the head of the NPL linear accelerator in order to calculate phase space spectra for all the standard photon qualities (see Figure 3). All of the material in the head of the linear accelerator will cause a certain amount of attenuation of the beam that is known as the inherent filtration. The NPL linear accelerator differs from typical clinical accelerators in that there is significantly less inherent filtration in the beam. In order to match the NPL beam more closely to a

[(ii)] Parameter Reduced Electron - Step Transport Algorithm
[(iii)] Pre-processor for EGS4
[(iv)] Extensions to the EGS4 system in the form of user-codes, PEGS4 data sets and other enhancements developed at NPL.

clinical beam additional filtration can be placed in the beam. The beam is described as lightly filtered (L) when only the inherent filtration is present in the beam and heavily filtered (H) when additional filtration is placed in the beam.

These codes store the full phase space information (that is, the energy, position, direction cosines, charge and weight) of each particle striking a predefined scoring plane that is perpendicular to the beam axis. These user-codes have been validated extensively by comparing $TPR_{20/10}$ values for calculated spectra with measured values. Depth dose curves for measured and calculated spectra have also been compared and good agreement has been found. See Appendix 1 for further details.

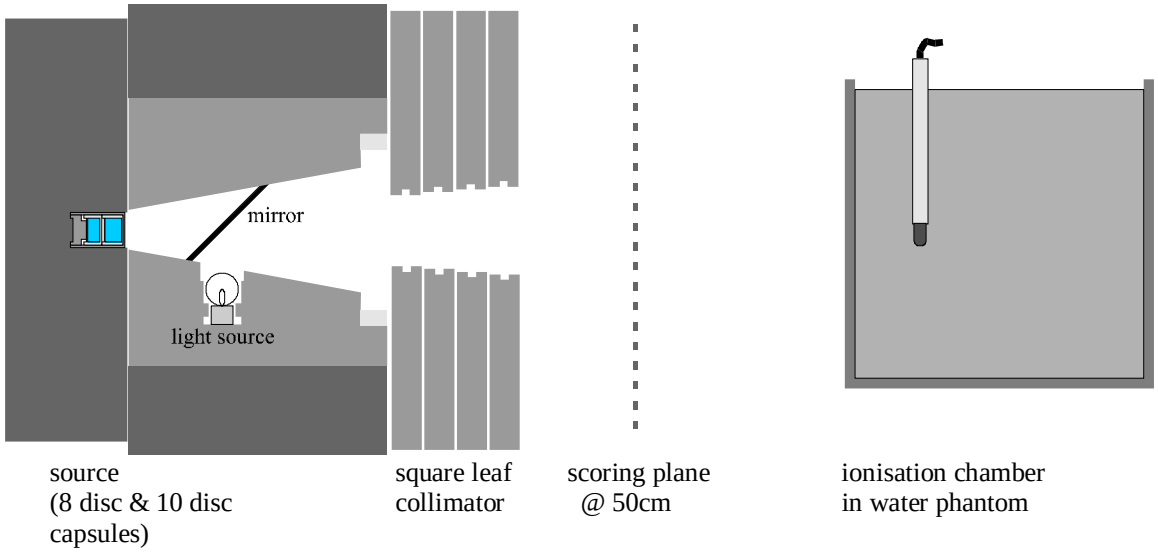

Figure 2: NPL Mobaltron ^{60}Co unit: schematic

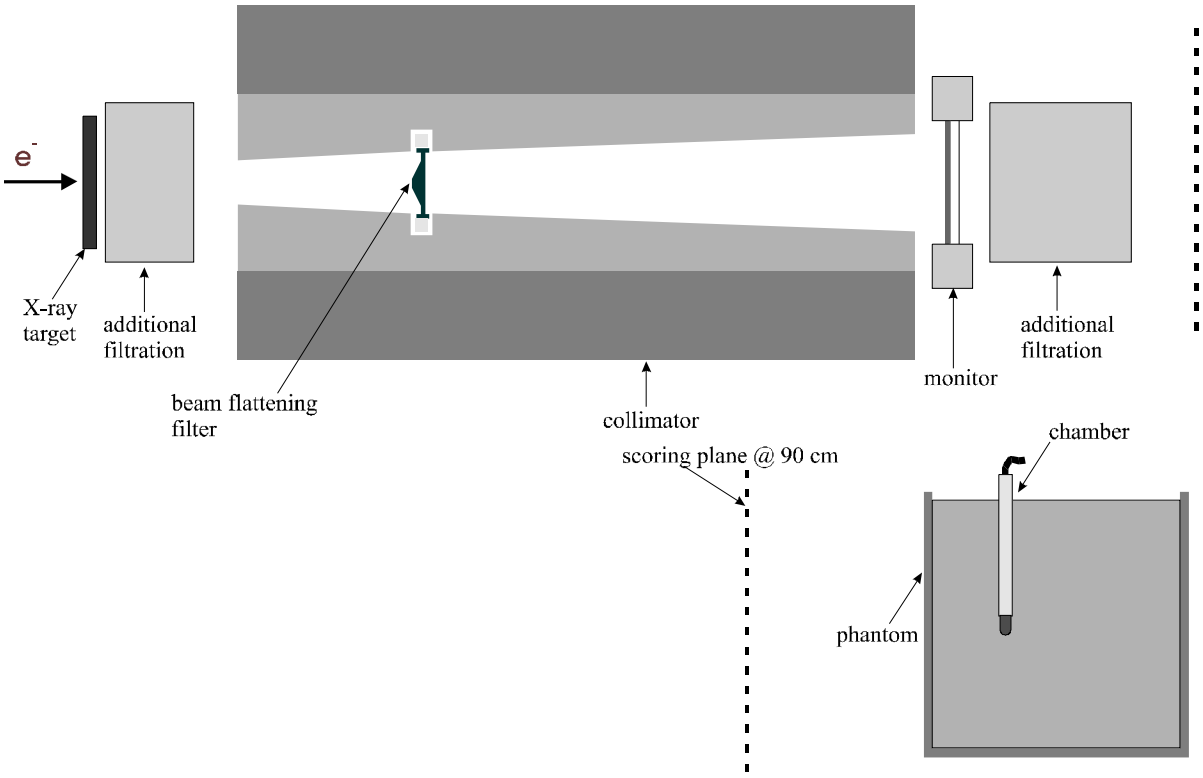

Figure 3: NPL Linear Accelerator (NPL LINAC): schematic

A new EGS4 user-code PHSCHAM (NPLEGS Prototype Version 1.10) was developed which uses as input the incident phase space information calculated by MOBALTRN and NPLLINAC to simulate the passage of electrons and photons through a cubic phantom. This code stores the full phase space information, the source particle number and an appropriate random number seed of each particle striking a specified thimble shaped volume (i.e. a cylinder with a hemisphere at one end) at a particular depth in the phantom (see Figure 4). PHSCHAM can oversample the list of stored particles and so the source particle number is the record number of the particle in the incident phase space file. The random number seed that is used by DOSCHAM is derived from the seeds of the RANMAR[(v)] random number generator used in PHSCHAM.

Particle information is stored on the specified scoring plane, A. PHSCHAM then reads this information and transports the particles to B, the front face of the phantom. The extra slab on the front face of the phantom allows the phantom to be placed at any distance from the source. PHSCHAM then transports the particles through the phantom and stores the phase space information, the source particle number and an appropriate random number seed for each particle striking the surface of the thimble shaped volume, C.

[(v)] Marsaglia long sequence random number generator

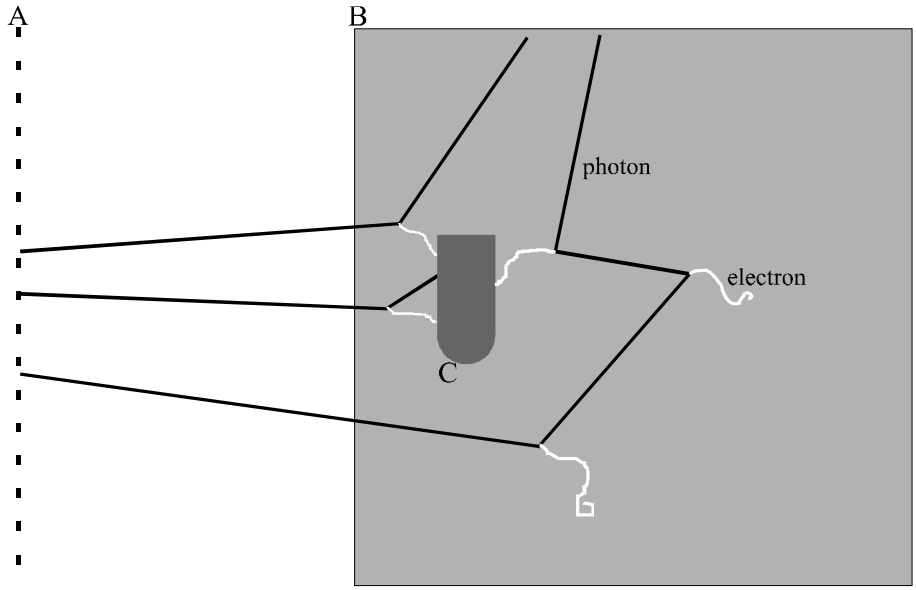

Figure 4: Shows the photon and electron particle tracks within a PHSCHAM calculation

Another EGS4 user-code DOSCHAM (NPLEGS Prototype Version 1.41) was developed to read in the phase space information generated by the user-code PHSCHAM to calculate the dose deposited to the internal regions of the thimble shaped geometry. The internal structure of the thimble shaped volume is made up of a series of cylinders, slabs and hemispheres (see Figure 5). DOSCHAM can also perform dose calculations using the phase space files generated by MOBALTRN or NPLLINAC as input directly. The code divides each dose calculation into 20 independent statistical bins from which the mean dose and standard error of the mean are determined. The source particle number assigned by PHSCHAM is used to ensure that a particle and all its' progeny are placed in the same statistical bin. DOSCHAM uses a generic 32-bit[vi] random number generator with the random number seed stored in the phase space file generated by PHSCHAM to initialise each particle. On subsequent samples of each particle this random number seed is updated to the 128th seed in the series so that each particle (although with the same incident parameters) is transported differently.

The particle information is stored by PHSCHAM on the surface of the thimble shaped volume, C. DOSCHAM reads in this information and then transports the particles for the remainder of each history throughout the whole geometry (i.e. the thimble and phantom). The code calculates the dose deposited in the internal regions of the thimble shaped volume.

[vi] The generic 32-bit RNG distributed with the original VAX version of EGS4 was used here

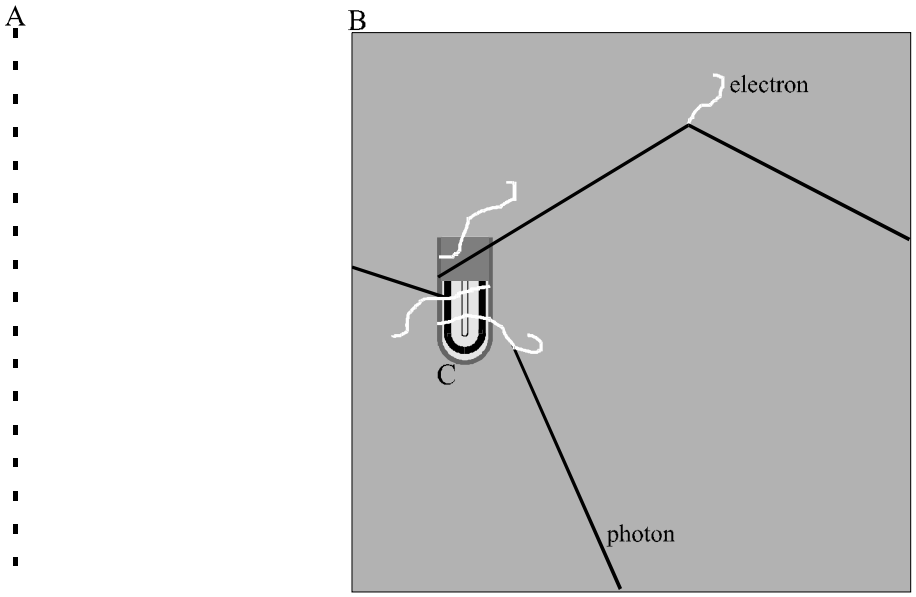

Figure 5: Shows the photon and electron particle tracks within a DOSCHAM calculation

If DOSCHAM uses particle information that has been stored on the surface of the thimble shaped volume and the particle list is over-sampled, time is saved as particles that do not strike the surface of the volume are only tracked once within the PHSCHAM calculation. Therefore there is a reduction in the time a simulation will take before the same uncertainty in the dose is reached. The calculations documented in this report require the ratio of doses from two similar simulations that use the same phase space information generated using PHSCHAM. The random number seed stored with this information is used to initialise each particle. This means that the transport in both simulations will be more closely correlated than if the calculated spectra had been used directly. In order to determine the ratio of the doses from the two simulations a FORTRAN program, DRATIO (version 3.06), was used. This program takes the ratio of the doses in each statistical bin, for each region of interest in the thimble shaped geometry and determines their mean and the standard error of the mean (SEOM). Taking the ratio of doses in each statistical bin instead of determining the ratio of the mean doses maximises the correlation between the dose calculations. This correlation between the calculations is optimised when the transport within the thimble shaped volume is similar for each simulation, which can be achieved by keeping the densities of the materials the same. By using the same phase space information for each calculation and storing the dose deposited by each particle according to its' source particle number typical reductions obtained in the SEOM of the dose ratio are 0.6% for ^{60}Co and between 0.3% for low energy X-rays up to about 1.0% at higher energies for the same number of incident particles.

For all EGS4 calculations the material information is read in from data sets generated using PEGS4. These data sets contain information on all materials used including their density, composition and electron and photon cross-sections over a selected energy range. The transport parameters AE[(vii)], UE[(viii)], AP[(ix)] and UP[(x)] are set within the PEGS4 input files which are used to create the data sets.

[(vii)] The minimum (total) electron energy required for explicit δ-ray production
[(viii)] The maximum (total) electron energy
[(ix)] Photon equivalent of AE
[(x)] The maximum photon energy

3. Calculation of the Absorbed Dose Calibration Factors

3.1 Overview

The absorbed dose calibration factor, N_w, for a chamber at depth in a water phantom in photon quality, Q, is given by: -

$$N_w = \frac{D_w}{D_{ch}} \tag{3.1}$$

Where: -

D_w is the dose to the water in the absence of the chamber.

D_{ch} is the dose to the chamber cavity in photon quality, Q.

D_w can be expressed as: -

$$D_w = D_{we} \cdot k_{dc} \tag{3.2}$$

Where: -

D_{we} is the dose to the chamber cavity in quality Q, when each chamber material has been replaced with water of the same density (i.e. a water equivalent chamber).

k_{dc} is a displacement correction that accounts for the displacement in the point of measurement in the cavity when water equivalent chamber materials are replaced with normal density water.

Hence,

$$N_w = \frac{D_{we}}{D_{ch}} \cdot k_{dc} \tag{3.3}$$

The absorbed dose calibration factor, N_w, can therefore be determined as follows. Firstly simulations were made of a stemless NE2561 ion chamber at various depths in a water phantom in photon quality Q to find the dose to the chamber cavity, D'_{ch}. As the chamber geometry included only 3 mm of stem material adjacent to the air cavity measured values of the stem scatter correction, k_{ssc}, in various beam qualities were interpolated and applied to the dose to the cavity, D'_{ch}.

Therefore,

$$D_{ch} = D'_{ch} \cdot k_{ssc} \tag{3.4}$$

Further simulations then determined the dose to the cavity of a water equivalent chamber, D_{we}. Also, derived values of the displacement correction, k_{dc}, in various beam qualities were interpolated and applied to the dose to the water equivalent chamber D_{we}. So the absorbed dose calibration factor, N_w, can be expressed as: -

$$N_w = \frac{D_{we}}{D'_{ch}} \cdot \frac{k_{dc}}{k_{ssc}} \tag{3.5}$$

3.2 Simulation Geometry

Nominal dimensions for the simulation geometry of the NE2561 ion chamber were used for these calculations. This was sufficient as at high energies the chamber response is not so sensitive to constructional details. See Appendix 3 for a list of the materials used in this work with their density and composition. The specification of Baltic amber[6] was used for amber, although ideally, the composition of the amber pellets used in the manufacture of NE2561 chambers should have been determined and used instead. Again, this is of less importance at high energies; see Section 4 for an estimate of the associated uncertainty.

The simulation geometry used to represent the cubic water phantom included an extra slab on the front face of the phantom. This allowed any differences between the scoring planes (within the incident spectrum calculation) and the front face of the phantom to be accounted for. For X-ray energies up to and including 10 MV and for ^{60}Co γ-radiation measurements are made with the chamber placed at a depth of 5 cm and for all X-ray energies above 10 MV the chamber is placed at a depth of 7 cm. The simulations modelled the chamber at these measurement depths. The source to chamber distance is 95 cm for ^{60}Co γ-radiation, 125 cm for X-ray energies up to 10 MV and 127 cm for all other X-ray energies.

The chamber simulation geometry matches the actual construction quite closely. The only major difference which may affect the spectrum is that only 3 mm of stem material adjacent to the air cavity has been modelled in order that the surface of the scoring volume in the PHSCHAM calculation is as close to the dose scoring regions as possible. This means that subsequent dose calculations using the same phase space information are more closely matched. All other differences in the geometries are minor and should not affect the dose scored in the internal regions at these energies.

3.3 PEGS4 Data sets

Within the PEGS4 input files the values of AE and AP were set to 0.516 MeV and 0.005 MeV for the air inside the chamber and 0.700 MeV and 0.010 MeV for the water surrounding the chamber. Values of AE and AP were set to 0.521 MeV and 0.010 MeV for all other materials. Values of UE and UP were set to 20.511 MeV and 20.0 MeV for all materials. The IAPRIM[7] and EPSTFL[8] options that are set within the PEGS4 input files were used. The IAPRIM option normalises the bremsstrahlung cross-sections so that PEGS4 gives the same radiative stopping power for electrons as given in ICRU Report 37[9]. The EPSTFL option allows the user to input an arbitrary density-effect correction for use in calculating electron and positron collision stopping powers. The density effect corrections were obtained using the program EPSTAR[(xi)] (S.M. Seltzer - version 2.0B) and these values were then used in conjunction with the PEGS4 input files to create the material data sets.

For the simulations calculating the response of the water equivalent chamber the materials specified used the density effect corrections for normal density water. This is because the displacement correction, which is applied to account for the differences between a water equivalent chamber and replacing the chamber with normal density water, corrects for the density and not the properties of the media.

[(xi)] Calculates stopping power (collisional, radiative and total), CSDA ranges, bremsstrahlung yield for electrons (or positrons) with kinetic energies from l keV to 10 GeV and the mean excitation energy of the material

3.4 Method of Calculation

3.4.1 Dose Ratios

The EGS4 user-code MOBALTRN was used to calculate a ^{60}Co γ-radiation phase space spectrum using a 6.0 x 6.0 aperture setting in order to give a 10 cm x 10 cm field at 95 cm. The scoring plane was defined to be at 50 cm from the source. The EGS4 user-code NPLLINAC was used to calculate all standard NPL (L and H) X-radiation phase space spectra for the therapy level calibration set-up. Phase space spectra for these standard NPL qualities were determined at a distance of 90 cm from the source. Only spectra for certain qualities, (4, 6, 8, 10 and 19 MV (H) and 4 and 6 MV (L)), were used in the calculation of N_w as these calculations can be very time consuming.

The EGS4 user-code PHSCHAM used spectra calculated by the user-codes MOBALTRN and NPLLINAC as input to calculate the phase space spectra incident on the surface of the chamber within a 30 cm cubic water phantom. For each photon beam quality two dose calculations were performed where the simulation geometry in both cases was identical. The first calculation determined the dose scored to the air cavity of the chamber (plus waterproof Perspex sheath) in a water phantom. The second calculation was identical except that all materials were replaced with water of the same density as the original material, (a water equivalent chamber). By keeping the density of the water the same as the materials in the first calculation the electron transport within the two simulations is very similar.

At present within EGS4 there are many approximations in the electron transport routines. The non-random uncertainties introduced by these approximations may be reduced by matching simulation geometries and taking ratios of doses. This represents the first part of the calibration factor, in Equation 3.5, which is the ratio of the response of the water equivalent chamber to the response of the stemless chamber when all materials are present, D_{we}/D'_{ch} .

The presence of any b_{min}[(xii)] dependency in the response of the chamber and water equivalent chamber was investigated. Absorbed dose calculations in 4 MV (H) X-radiation at a depth of 5 cm in a water phantom, were performed with DOSCHAM using different values of b_{min}. The calculations showed a difference in the dose values of about 2% for sets of simulations using b_{min} values of 3.0 and 5.428 (the maximum b_{min} value allowed by PRESTA). On comparison of dose ratios, for each value of $b_{min,}$ agreement was found to within 0.1% with uncertainties on the dose ratios of less than 0.3% (at 1σ). Therefore, when calculating the absorbed dose calibration factor for a chamber in a water phantom, pairs of calculations used the same b_{min} value in order that any non-random errors in the absorbed doses would be reduced when taking the dose ratio.

Further calculations were performed to investigate for the presence of any ESTEPE[(xiii)] dependency in the response of the chamber in ^{60}Co γ-radiation, 4 and 6 MV (L and H) and 19 MV (H) X-radiation. Absorbed dose calculations were performed for the chamber and for the water equivalent chamber using a fixed ESTEPE restriction of 2%. There was found to be some dose dependence with ESTEPE at all energies when these results were compared with results from simulations using no ESTEPE restriction. The calculations showed that for an unrestricted ESTEPE and an ESTEPE restriction of 2% the absorbed dose results differed by about 2% with uncertainties on the doses of 0.8 - 1.5% (at 1σ). On comparison of the dose ratios for these simulations the results were found to differ by 0.7% where the uncertainties on the dose ratios were 0.3% (at 1σ). These results show that there may be a small ESTEPE dependence in the dose ratio calculation[10]; therefore all calculations used an ESTEPE

[(xii)] A parameter used by PRESTA to restrict the minimum electron step size near a boundary
[(xiii)] Maximum fractional energy loss per step due to the continuous slowing down of charged particles

restriction of 2%.

3.4.2 Stem Scatter Correction, k_{ssc}

In the PHSCHAM/DOSCHAM simulations presented in this report the chamber geometry was simplified by only including 3 mm of stem material adjacent to the air cavity so that the phase space information could be recorded as close as possible to the dose scoring regions. A correction is therefore required to account for the increase in the response due to scatter from the stem material that has not been simulated. Measured values taken from Table A.14.7 of Reference 1 have been used. The measurements were made with a chamber in a polystyrene phantom (at an effective depth in water of 5 cm for X-ray energies up to 10 MV and for ^{60}Co γ-radiation and at 7 cm for all other X-ray energies) where a second dummy stem was brought into contact with the hemispherical end of the original chamber. It has been assumed that these measured values are the same as for a water phantom. The measured stem scatter corrections versus $TPR_{20/10}$ are shown in Figure 6. The points were fitted using a least squares fit and the stem scatter corrections for the beam qualities of interest were calculated using the fit to the points. Values of k_{ssc} for the photon qualities of interest can be found in Table 2.

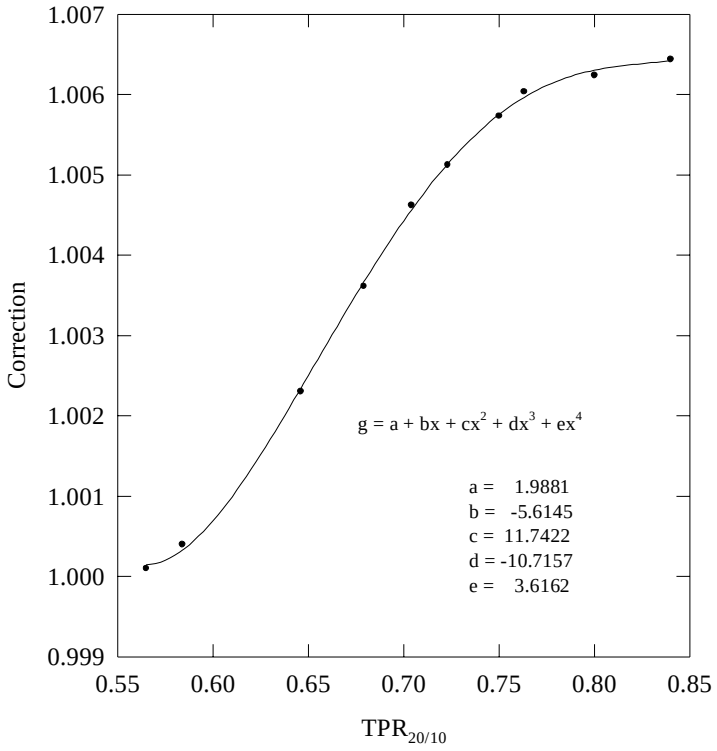

Figure 6: Variation of Stem Scatter Correction with $TPR_{20/10}$

3.4.3 Displacement Correction, k_{dc}

The aim of the calculations presented in this report is to obtain the chamber absorbed dose calibration factor, N_w, from the ratio of the response of the actual chamber to the response when the chamber materials have been replaced with normal density water. The dose calculations presented in Section 3.4.1 modelled a water equivalent chamber instead of replacing the chamber with water of density 1 gcm^{-3}. A further correction is therefore required to account for this simplification. In this work the

displacement correction, k_{dc}, is defined as the ratio of the chamber response when all materials have been replaced with normal density water to the response of the water equivalent chamber. Further calculations were made to determine the displacement correction for a chamber at depth in a water phantom in the various beam qualities. Values of the calculated displacement corrections were compared with values taken from Table A.14.6 of Reference 1 that were derived from data given in the AAPM dosimetry protocol (AAPM 1983). A small correction was added (<0.1% for all qualities) to the derived corrections to account for the difference in attenuation of the chamber sheath and water it displaces. These corrections are assumed to be applicable here. There was found to be a discrepancy between the derived and calculated values of between 3 - 5% with uncertainties of between 0.3 - 0.9% (at 1σ). This discrepancy is likely to be due to the lack of correlation in the two dose calculations (due to large differences in the density of the cavity materials) resulting in little or no cancellation of the non-random effects in the electron transport routines. Therefore, values of the required displacement correction, k_{dc}, were determined by interpolation of the derived values of the displacement correction against $TPR_{20/10}$, as shown in Figure 7. The points were fitted using a least squares fit and the displacement corrections for the beam qualities of interest were calculated using the fit to the points. Values of k_{dc} for the photon qualities of interest can be found in Table 2.

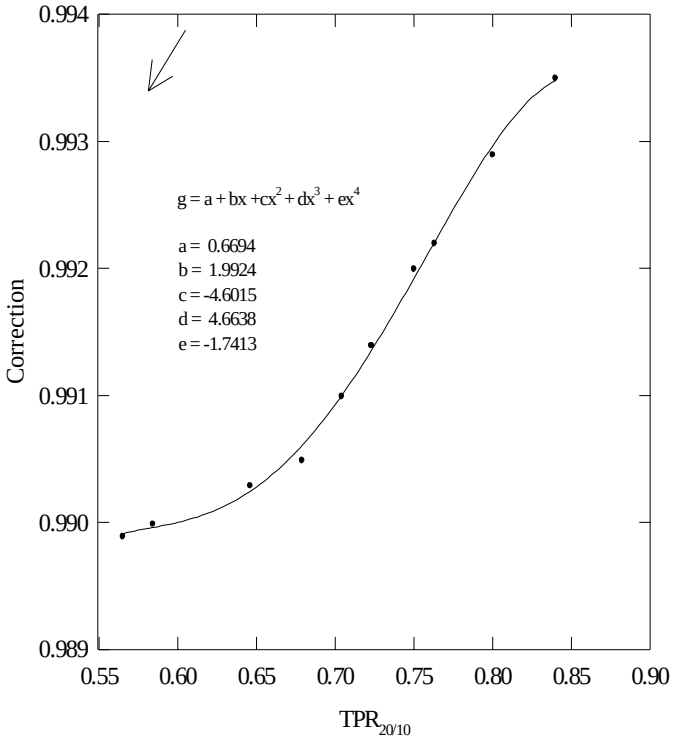

Figure 7: Variation of Displacement Correction with $TPR_{20/10}$

4. Uncertainties

As there are a number of non-random uncertainties that are present in the calculated values for the absorbed dose calibration factors it is necessary to understand the nature of these uncertainties and to make an estimate of their size. This section will therefore consider the uncertainties present in the calculations due to the displacement correction, the stem scatter correction, errors in the transport physics within EGS4 and in the cross sectional data. Random uncertainties are calculated by the EGS4 user-codes.

(All % standard uncertainties)	Type A (random)	Type B (non-random)
D_{we}/D'_{ch}	0.34	0.1
k_{dc}	-	0.25
k_{ssc}	-	0.10 (0.05)*
Total	0.34	0.29 (0.27)*
Overall	0.45 (0.44)	

*Values given in brackets are for ^{60}Co.

Table 1: Table of Uncertainties

Errors in the electron transport physics within EGS4 and their size are generally determined by the choice of ESTEPE, b_{min} and any transport parameters. Calculations have been made to investigate for any dose dependence on b_{min} or ESTEPE. It was found that the absolute dose calculations do depend on b_{min} and possibly ESTEPE. When values for b_{min} are kept the same and a restricted value of ESTEPE is used these uncertainties are reduced when taking the dose ratio, as no significant dependence within the obtained random uncertainty is apparent. Errors may also be introduced due to the uncertainty on the cross-sectional data used in EGS4. As the dominant photon interactions within the EGS4 simulations at high energies will be due to Compton scatter and pair production the uncertainty on the cross sectional data will be about 2%. However it is reasonable to assume that the effects are reduced when taking the dose ratio, as there will be some cancellation. An overall non-random uncertainty of 0.1% (at 1σ) is considered pessimistic.

Derived values for the displacement correction have been used for these calculations. Table 4.3 of Reference 1 gives an estimated non-random uncertainty of 0.15% (at 1σ) as being conservative for those values. As the values for the displacement correction were derived for different $TPR_{20/10}$ values than are of concern here, in order to obtain the displacement corrections for the values of interest, a suitable fit was applied to the data from which the relevant values were determined. This means that a further small uncertainty will be introduced in the fitting of this line. These values for the displacement correction include an effect due to displacement by the stem. For the calculations presented here the simulation geometry only includes 3 mm of stem material adjacent to the air cavity, and so a further uncertainty will be present in the displacement correction. Therefore an overall uncertainty on the displacement correction of 0.25% (at 1σ) is considered reasonable.

Values for the stem scatter correction were obtained by making measurements in a polystyrene

phantom using a second dummy stem in addition to the actual chamber stem. However, in this work, a correction for having no stem is required. This means that there is a small uncertainty in the correction due to the second order scatter effects that will have been included in the measurements. There will also be an additional uncertainty as measurements were made in a polystyrene phantom and the required correction is for a water phantom. Table 4.3 of Reference 1 gives an estimated uncertainty for the stem scatter correction of 0.01% (at 1σ) in ^{60}Co γ-radiation and 0.05% (at 1σ) in all other X-ray qualities. The values for the stem scatter correction were measured for different $TPR_{20/10}$ values than are of concern here. In order to obtain the stem scatter corrections for the values of interest a suitable fit was applied to the measured data from which relevant values were determined and so a further uncertainty will be introduced in the fitting of this line. The overall uncertainty on the stem scatter correction should therefore be no more 0.05% (at 1σ) in ^{60}Co γ-radiation and 0.1% (at 1σ) in all other X-ray qualities.

A total non-random uncertainty on the absorbed dose calibration factor of 0.29% (at 1σ) for all the X-ray qualities calculated here and 0.27% (at 1σ) for ^{60}Co γ-radiation plus a maximum random uncertainty of 0.34% for all qualities is therefore considered conservative. The value of the total uncertainty at 1σ is therefore 0.45% for all X-ray qualities calculated here and 0.44% for ^{60}Co. The total uncertainty has been obtained by combining the non-random and random uncertainties in quadrature.

5. Results

Values of the calculated dose ratio, D_{we}/D'_{ch}, and the derived displacement and stem scatter corrections, k_{dc} and k_{ssc}, are given in Table 2 for all the photon qualities of interest in this work. The random uncertainties in D_{we}/D'_{ch} are given at the 1σ level. Values of the calculated absorbed dose calibration factors, N_w, are given in Table 3 for each photon quality. The absorbed dose calibration factor is the product of the dose ratio and the displacement and stem scatter corrections as given in Equation 3.5.

Values of the measured absorbed dose calibration factor, k_Q, for a NE2561 ion chamber, given in Table 3, are normalised by the absorbed dose calibration factor for ^{60}Co. In order to compare the calculated and measured values it was necessary to normalise the calculated values in a similar way. This normalisation, however, adds an extra uncertainty component (the total uncertainty on the absorbed dose calibration factor for ^{60}Co) to the total uncertainty in all the derived absorbed dose calibration factors. Therefore, the values for the calculated absorbed dose calibration factors have been scaled to fit the measured k_Q values so that the total uncertainties on these values are more realistic. This was done using the graphics package SigmaPlot[(xiv)] to determine a line of best fit to the measured results. The equation describing this line was then scaled to best fit the calculated results for all the beam qualities with heavy filtration. This scaling factor was then used to normalise all of the calculated results so that the experimental values of k_Q could be directly compared with the calculated calibration factors (see Figure 8).

[(xiv)] SigmaPlot for Windows, Version 4.01

Quality	($TPR_{20/10}$)	Dose Ratio $\frac{D_{we}}{D'_{ch}}$	SEOM (%)	Displacement Correction k_{dc}	Stem Scatter Correction k_{ssc}
^{60}Co	(0.568)	1.1212	0.12	0.9899	1.0002
4 MV (L)	(0.584)	1.1145	0.16	0.9900	1.0003
4 MV (H)	(0.621)	1.1131	0.06	0.9901	1.0014
6 MV (L)	(0.646)	1.1170	0.16	0.9902	1.0023
6 MV (H)	(0.670)	1.1081	0.19	0.9905	1.0033
8 MV (H)	(0.717)	1.1031	0.20	0.9912	1.0050
10 MV (H)	(0.746)	1.0936	0.34	0.9918	1.0057
19 MV (H)	(0.790)	1.0765	0.24	0.9928	1.0063

Table 2: Calculated dose ratios and SEOMs, stem scatter and displacement corrections

Quality	($TPR_{20/10}$)	Calculated Absorbed Dose Calibration Factors, N_w	Normalised Absorbed Dose Calibration Factors	Measured Absorbed Dose Calibration Factors, k_Q
^{60}Co	(0.568)	1.1097	1.0073	1.0000
4 MV (L)	(0.584)	1.1030	1.0012	-
4 MV (H)	(0.621)	1.1006	0.9990	0.9986
6 MV (L)	(0.646)	1.1035	1.0017	-
6 MV (H)	(0.670)	1.0939	0.9930	0.9941
8 MV (H)	(0.717)	1.0880	0.9876	0.9885
10 MV (H)	(0.746)	1.0786	0.9791	0.9815
12 MV (H)	(0.758)	-	-	0.9781
16 MV (H)	(0.779)	-	-	0.9717
19 MV (H)	(0.790)	1.0621	0.9641	0.9670

Table 3: Calculated and measured absorbed dose calibration factors

6. Comparison of Calculated factors with Measured k_Q Values

Values of the measured absorbed dose calibration factors were reproduced to within 2σ for all beam qualities when the calculated results were scaled as described in Section 5. The gradient of the line of best fit to the calculated results is steeper at higher energies than the line of best fit to the measured results and the calculated value for ^{60}Co is significantly higher than expected.

Experimental results show that the absorbed dose calibration factors for 4 and 6 MV (L) fall about 0.6% below the calibration curve for beam qualities with heavy filtration (see Figure 1). However, the calculated calibration factors for 4 and 6 MV (L) do not follow this behaviour and lie within 1σ of the line of best fit to the calculated calibration curve for beam qualities with heavy filtration.

At present using the techniques presented in this report with the current version of EGS4 it is not possible to distinguish between the light and heavy filtration data at low MV energies, therefore, it is not yet possible to investigate the causes of this observed difference in the measured results.

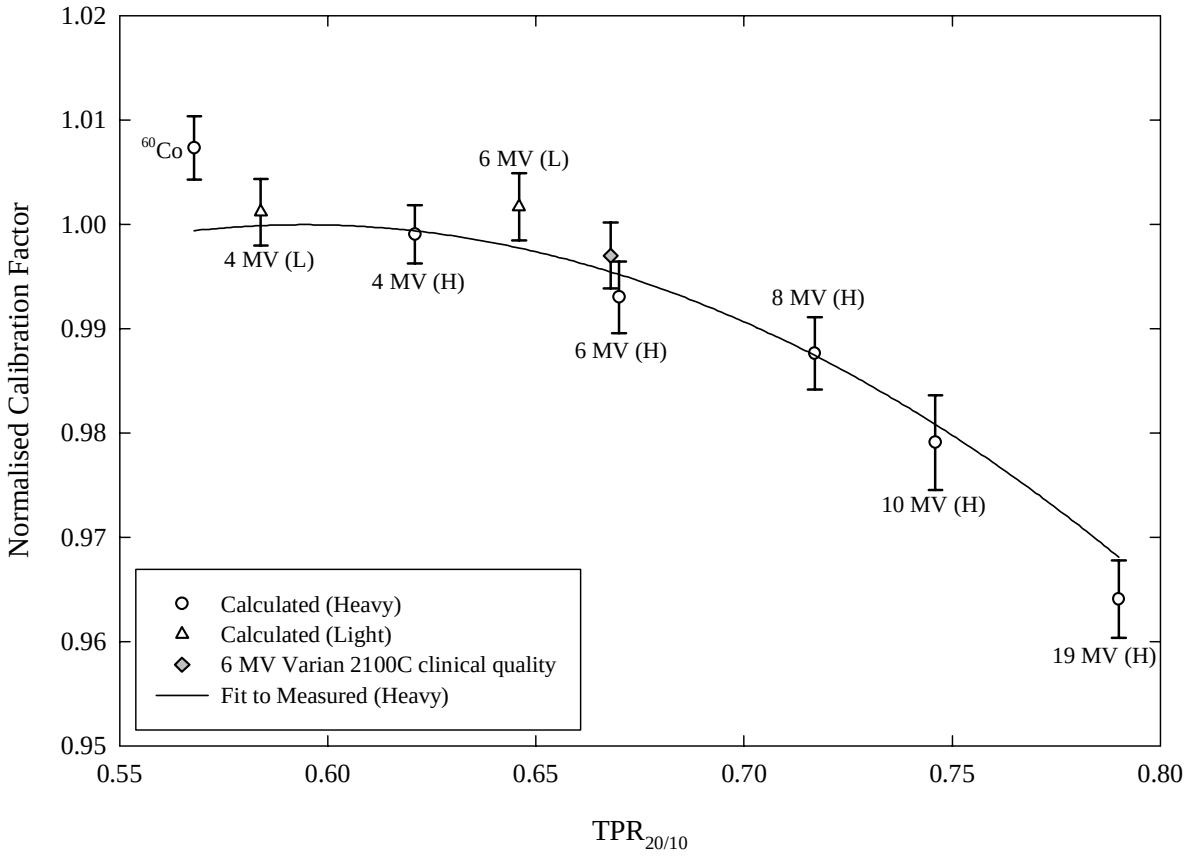

Figure 8: Variation of Calculated and Measured absorbed dose calibration factors with $TPR_{20/10}$ (Error bars show 1σ uncertainty)

7. Comparison of NPL and Clinical Results

7.1 Simulation of a Varian 2100C

Colleagues at Velindre Hospital simulated a Varian 2100C clinical accelerator using the EGS4 user-code BEAM (part of OMEGA-BEAM system[11]). The full phase space information was supplied for a 6 MV X-ray quality set to give a 10 cm x 10 cm field at 100 cm from the target. The simulation geometry comprised five component modules including the target, primary collimator, flattening filter, shielding ring and jaws. A 6 MeV electron pencil beam was simulated incident on the target in which bremsstrahlung splitting was turned on and the number of splits per initial bremsstrahlung photon was set to 20. An air slab was included up to the scoring plane that was defined to be at 50 cm from the target. The value of ECUT[(xv)] was set to 700 keV in all regions. The output from the simulation was in a similar format to the NPLLINAC/MOBALTRN spectra and a simple conversion was required in order to bin the spectra in a similar way. This binned phase space spectrum was compared with phase space spectra for 6 MV NPL X-ray beams with light and heavy filtration which were determined using the code NPLLINAC (see Figure 9). It can be seen from Figure 9 that the addition of further filtration to the lightly filtered NPL beam improves the overall agreement between the calculated spectra for the NPL and clinical beams although the peak of the continuum of the NPL spectra occurs at a slightly higher energy.

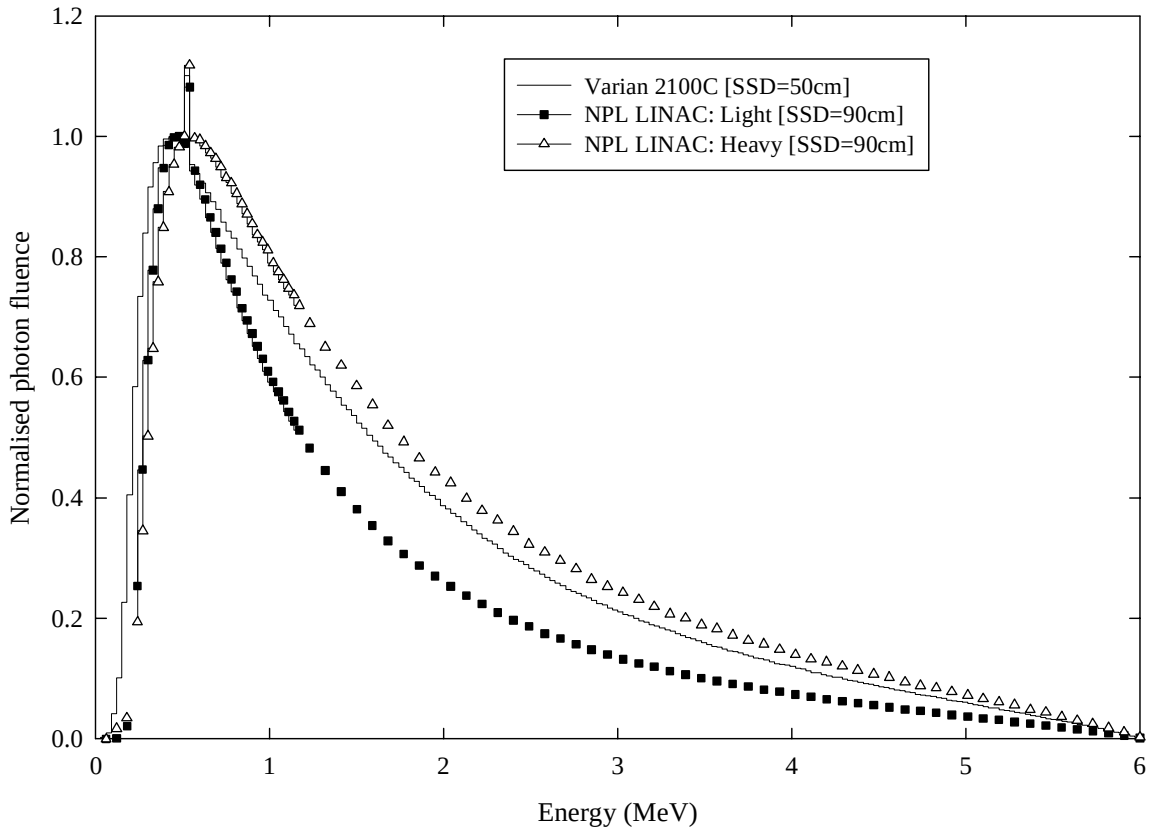

Figure 9: Photon fluence spectra: 6 MV X-rays [All spectra normalised to peak of continuum]

[(xv)] The cut-off (total) energy for charged particle transport

7.2 Depth dose curve for a Varian 2100C beam

The calculated spectra described in Section 7.1 were then used as input by the user-code DOSRZPAR in order to determine the depth dose curves (Figure 10) and $TPR_{20/10}$ for a 10 cm x 10 cm field at a depth of 10 cm in a 30 cm cubic water phantom (see Appendix 1 for further details).

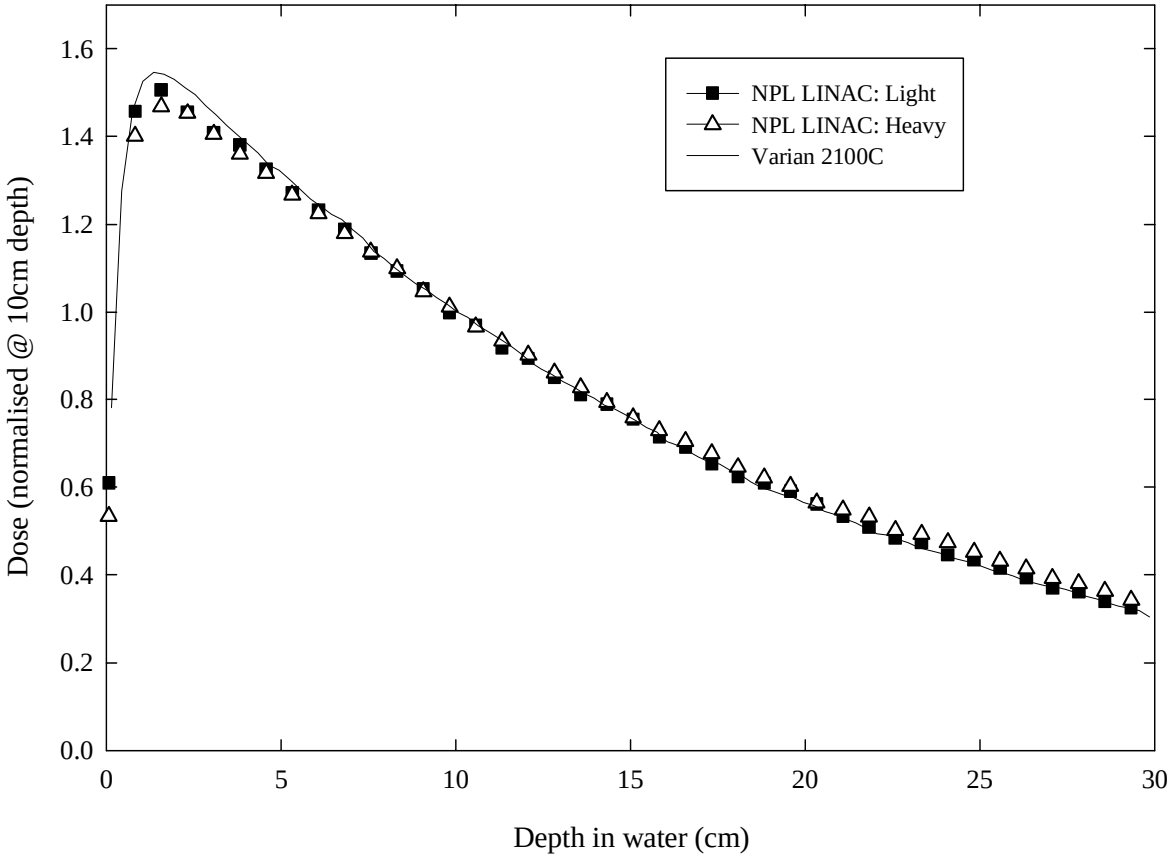

Figure 10: 6 MV X-rays: Depth Dose curves in Water

The calculated values of $TPR_{20/10}$ for the NPL 6 MV X-ray qualities with light and heavy filtration are 0.648 and 0.667 respectively for the standard collimator (10 cm x 10 cm field at 125 cm). These are in reasonable agreement with the quoted values of $TPR_{20/10}$, which are 0.646 and 0.670 respectively. The calculated value of $TPR_{20/10}$ for the 6 MV X-ray quality from a Varian 2100C LINAC is 0.668 for a 10 cm x 10 cm field at 100 cm (which is 0.2% less than the NPL 6 MV (H) value). The value of $TPR_{20/10}$ quoted in BJR supplement 25[12] for 6 MV X-rays (based on data sets for a range of machines) for a 10 cm x 10 cm field at 100 cm is 0.677.

PDD(10) and PDD(20) are defined as the percentage depth dose at 10 cm and 20 cm depths in the phantom. Values for PDD(10) and PDD(20) for the NPL and clinical beams were obtained directly from the calculated depth dose curves and corrected for a 10 cm x 10 cm field at 100 cm SSD (using corrections quoted in BJR supplement 25). Values of PDD(10) and PDD(20) for the NPL 6 MV (L) quality are 0.652 and 0.366 and for the NPL 6 MV (H) quality are 0.672 and 0.390. The calculated

values of PDD(10) and PDD(20) for the Varian 2100C X-ray beam are 0.665 and 0.383 and the values taken from BJR supplement 25 for 6 MV X-rays are 0.675 and 0.393 respectively.

It can be seen, therefore, that there is good agreement between the values of $TPR_{20/10}$, PDD(10) and PDD(20) for the NPL heavy and Varian 2100C X-ray qualities and the values predicted by BJR supplement 25 for 6 MV X-rays.

7.3 Calibration factor for a Varian 2100C beam

The phase space spectrum for the clinical beam was then used as input by PHSCHAM to calculate the phase space spectrum incident on the surface of a NE2561 ion chamber within a 30 cm cubic water phantom with the chamber at a depth of 5 cm in the phantom. The dose scoring code DOSCHAM then used this phase space spectrum to calculate the dose to the cavity of a stemless chamber with actual and water equivalent materials, as before. The simulation geometry details and the PEGS4 data sets used were the same as simulations for the NPL X-ray qualities. Stem scatter and displacement corrections were determined as described in Sections 3.4.2 and 3.4.3 and applied as given by Equation 3.5 to give the absorbed dose calibration factor, N_w. It can be seen from Figure 8 that there is good agreement between the calculated absorbed dose calibration factor for the clinical machine and the NPL calibration curve for heavy qualities.

8. Conclusions

All the calculated absorbed dose calibration factors agree with the corresponding experimental value to within 1-2 σ (total uncertainty) where 1 σ is 0.45%. The observed discrepancies between calculated and experimental values for the absorbed dose calibration factors are predominantly random in nature. Many of the non-random errors within the calculated absorbed dose values have been investigated and are greatly reduced when taking dose ratios. There was found to be a b_{min} dependency and possibly an ESTEPE dependency in the values of the absolute dose although the results showed no evidence of any b_{min} dependency in the dose ratio results within the obtained random uncertainties. However, the results did show that there maybe a small ESTEPE dependency in the dose ratio results, therefore a restricted ESTEPE of 2% was used.

The measured absorbed dose calibration factors, k_Q, for 4 and 6 MV X-ray qualities with light filtration are typically 0.6% below the corresponding calibration curve for X-ray qualities with heavy filtration. As the calculated factors have an associated total uncertainty of 0.45% (at 1 σ) it is not possible to see a significant difference between results with light and heavy filtration. For the differences to become apparent it would be necessary to reduce both the random and non-random uncertainties on the calculated results significantly. It may be possible to achieve this by increasing the size of the initial NPLLINAC and MOBALTRN phase space files, however, for qualities at low energies with heavy filtration these calculations are very time consuming. Alternatively modifying PHSCHAM and DOSCHAM to include an option for biasing the photons so that they are more likely to interact within the ion chamber geometry could reduce the uncertainties.

The ESTEPE and b_{min} dependencies that are present in the absolute dose results are only reduced when taking the ratio of the doses of two closely matched simulations. As a result, it has not yet proved possible to calculate the displacement correction using the Monte Carlo techniques described in this report. This is due to the fact that the two simulations necessary to calculate the displacement correction have media of very different densities in their respective sensitive volumes resulting in the particle transport being very different in these regions.

Unfortunately it was not possible to distinguish between the results for the light and heavy filtration with current EGS4 user-codes as the electron transport physics is not yet good enough for these types of applications. It is therefore not yet possible to investigate the cause of the observed variation of N_w with beam filtration in NPL beams; however, it may be possible with new electron transport routines in EGSnrc. These new routines should make it possible to calculate N_w directly without the need to resort to new techniques to reduce non-random uncertainties in the current code (e.g. matched geometries) and the reliance on derived data (e.g. displacement correction) and empirical data (e.g. stem scatter correction).

There was found to be a good match between NPL heavy and clinical beams for 6 MV X-rays. This was confirmed as the value of N_w for a Varian LINAC is close to the NPL calibration curve and the depth dose curves confirm that the addition of extra filtration to the NPL LINAC produces a closer match to a clinical beam.

9. Acknowledgements

The authors would like to Simon Duane and Karen Rosser for carrying out the experimental measurements of the absorbed dose calibration factors and Russell Thomas for carrying out experimental measurements of depth dose curves.

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Appendix 1: Validation of NPLLINAC & MOBALTRN

1.1 EGS4 user-code DOSRZPAR

The user-code DOSRZPAR is an NPL enhanced version of the standard user-code DOSRZ (which is part of the 1995 EGS4 Distribution). DOSRZPAR has been well tested and validated against the established code and calculates the dose to the internal regions of a cylindrical volume that is made up of a series of cylinders and slabs. It was therefore necessary to approximate the measurement set-up by a cylindrical water phantom with a radius chosen to give the same area as the front face of the phantom used in the measurements.

1.2 Comparison of Calculated and Measured Depth Dose Curves.

Firstly, comparisons of calculated and measured depth dose curves in water provided validation for the user-codes NPLLINAC and MOBALTRN. Depth dose curves were measured for a 10 cm x 10 cm field at a depth of 10 cm in a water phantom with a source to chamber distance of 125 cm. Measurements of ionisation against depth were made by scanning a chamber along the central axis of the water phantom. No conversion from ionisation to dose was made since it has been shown previously that the water-to-air stopping power ratio does not vary greatly with depth beyond the peak of the depth dose curve[13]. Simulations were carried out using DOSRZPAR for the same set up and a direct comparison of the results was made by normalising the two sets of results at a depth of 10 cm. See Figures A.1 - A.3 for plots of the relative dose versus depth in water for ^{60}Co γ-radiation, 4 MV and 19 MV (H) X-radiation. These plots show good agreement between calculated and measured results both in the build-up region and beyond the dose maximum. Part of the build-up region for the measured results occurs in the Perspex front face of the phantom so it was not possible to make measurements over this depth. As the chamber is placed at a depth of either 5 or 7 cm for the work presented in this report matching of the depth dose curves at these depths is not vital.

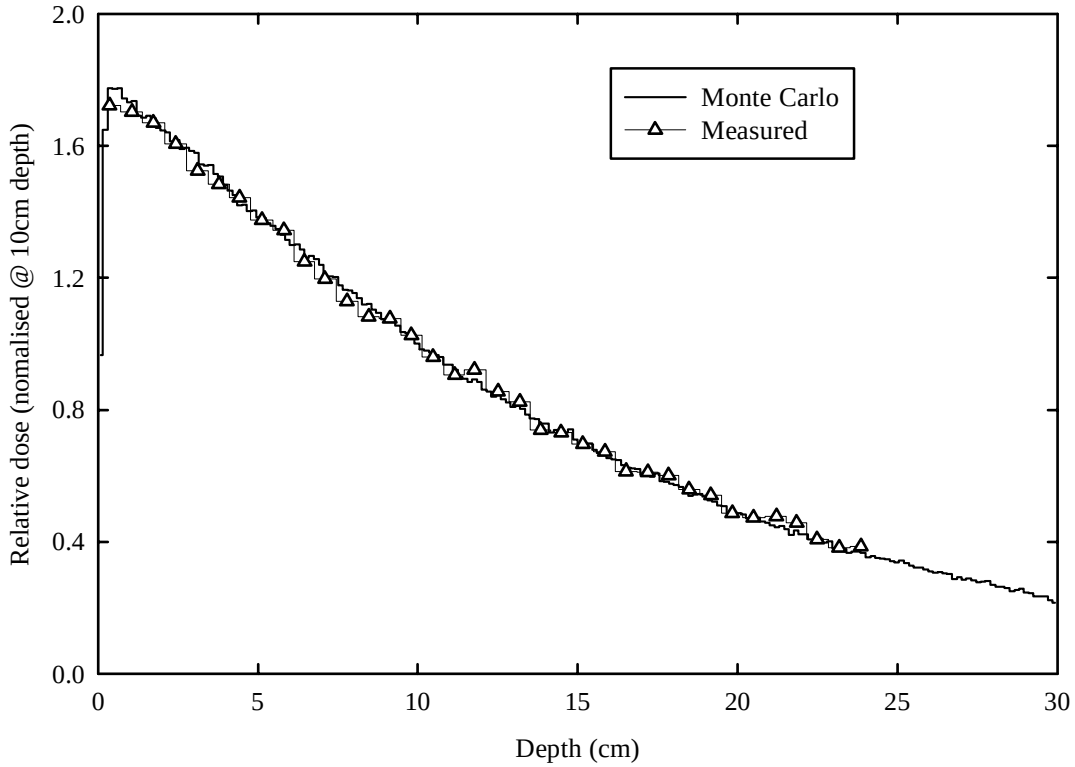

Figure A.1: NPL Mobaltron ^{60}Co unit: Depth dose curves in water

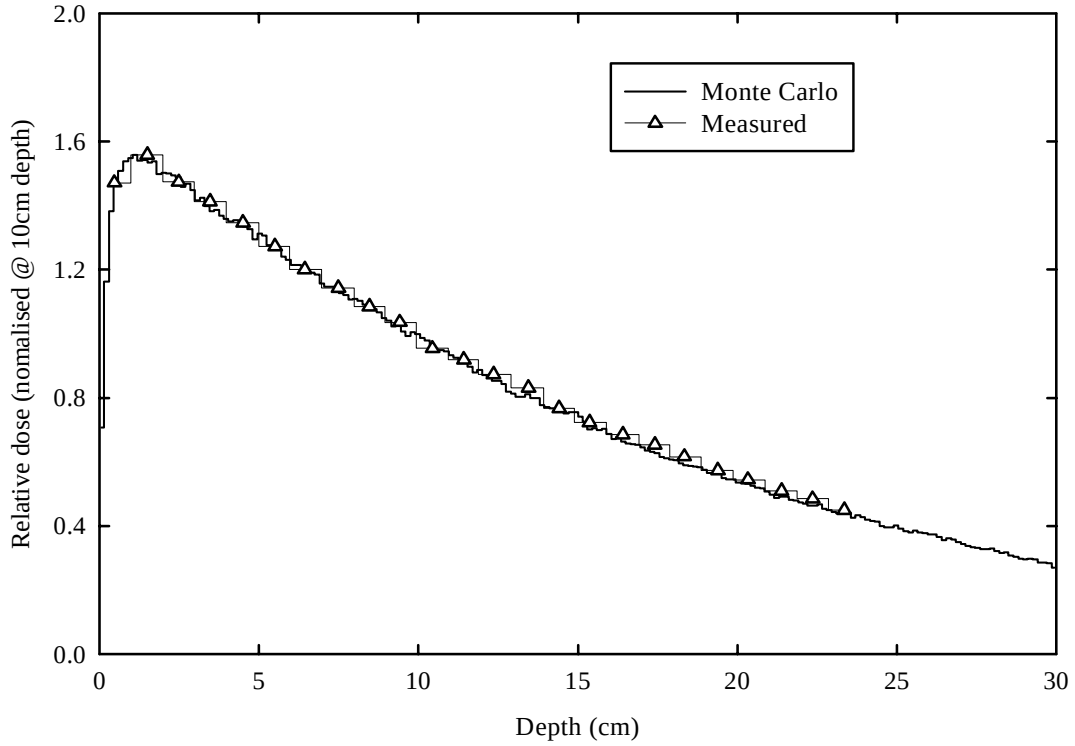

Figure A.2: NPL LINAC: 4MV (H) depth dose curves in water

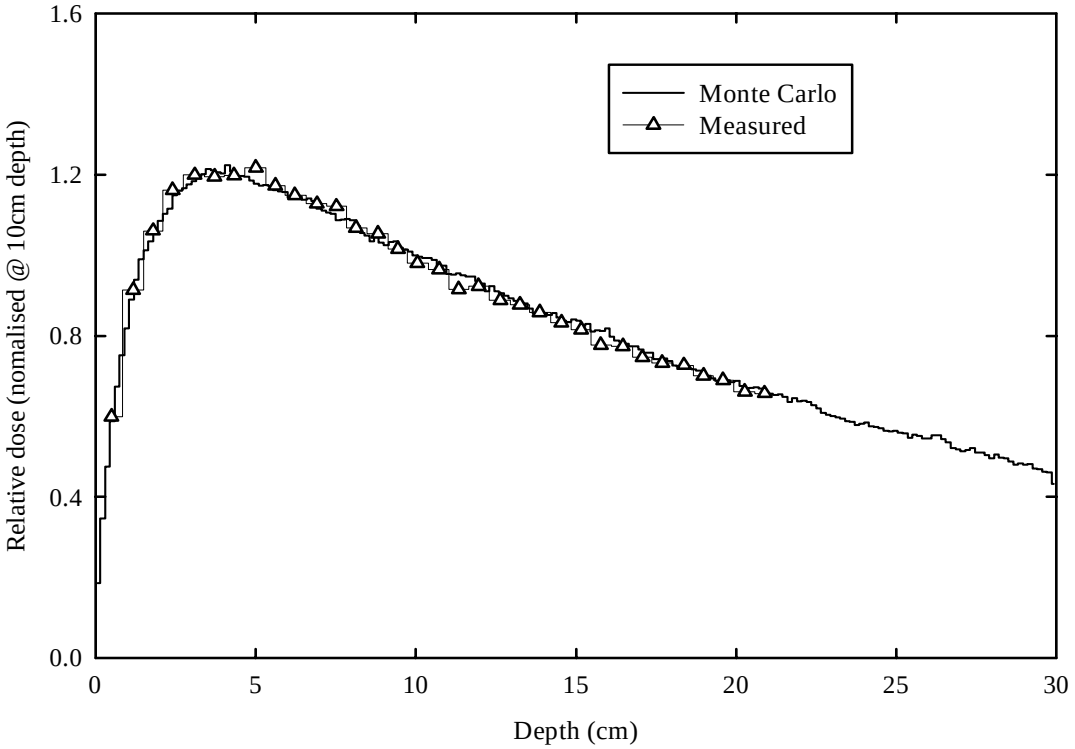

Figure A.3: NPL LINAC: 19MV (H) depth dose curves in water

1.3 Comparison of Calculated and Measured values of $TPR_{20/10}$

Further validation of the user-codes NPLLINAC and MOBALTRN was provided by determining $TPR_{20/10}$ for various photon spectra generated using these codes and comparing these calculated values with the corresponding experimental values. The fixed focal distance to give a 10 cm x 10 cm field was set to 100 cm for measurements made on the NPL Mobaltron and 125 cm for measurements made on the NPL LINAC. Monte-Carlo simulations were carried out using DOSRZPAR for the same set up.

Table A.1 gives the results from the calculations and compares the calculated values with measured values of $TPR_{20/10}$. The uncertainties quoted are the calculated values of the standard error on the mean (SEOM). The calculated values of $TPR_{20/10}$ for all qualities agree with their corresponding experimental values to within 2σ in the total random uncertainty. This implies that the techniques that were used to determine the photon spectra produced by the NPL Mobaltron and the NPL Linear accelerator are reliable. It should be noted, however, that differences between measured and calculated values of $TPR_{20/10}$ would be of greater significance at higher energies when plotting calibration factors against $TPR_{20/10}$ due to the shape of the calibration curve.

Quality	Measured $TPR_{20/10}$	Calculated $TPR_{20/10}$
^{60}Co	(0.567 ± 0.001)	(0.569 ± 0.001)
4 MV (L)	(0.588 ± 0.001)	(0.587 ± 0.001)
4 MV (H)	(0.621 ± 0.002)	(0.621 ± 0.001)
6 MV (L)	(0.648 ± 0.001)	(0.648 ± 0.001)
6 MV (H)	(0.666 ± 0.001)	(0.667 ± 0.002)
19 MV (H)	(0.790 ± 0.001)	(0.793 ± 0.001)

Table A.1: Measured and calculated values of $TPR_{20/10}$.

Appendix 2: Validation of PHSCHAM & DOSCHAM

2.1 Tests performed to check particle transport

The user-codes PHSCHAM and DOSCHAM were validated by various methods. Firstly, as these codes have an option to allow graphical output of particle histories, this output was examined using the graphics package EXHI2. This package was used to display and manipulate the particle histories to ensure that all of the histories were consistent with expectation. Individual particle tracks were looked at to ensure that there was no misalignment at boundaries and that conservation of momentum was kept at all times in the particle track. The point at which a particle was scored within PHSCHAM was also checked to ensure that it lay on the surface of the thimble shaped geometry. No discrepancies were found in any of the particle tracks.

The second method confirmed that a dose calculation with DOSCHAM using phase space spectra incident on the front face of the phantom (generated by NPLLINAC and MOBALTRN) agreed with the

same dose calculation but using the intermediate phase space spectra generated with PHSCHAM. Absorbed dose calculations were performed for an ion chamber where all chamber materials are present and where all materials have been replaced with water of the same density as the original material, (i.e. a water equivalent chamber). The simulations were carried out with the ion chamber placed at a depth of 7 cm in a water phantom in 19 MV (H) X-radiation. These calculations used identical transport parameters (i.e. AE, ECUT, AP, PCUT, ESTEPE and b_{min}). For all regions in the geometry except for the air cavity inside the ion chamber and the phantom region surrounding the chamber AE and ECUT were set to 0.521 MeV and AP and PCUT were set to 0.010 MeV. For the air cavity region inside the ion chamber AE and ECUT were set to 0.516 MeV and AP and PCUT were set to 0.005 MeV. For the phantom region outside the chamber AE and ECUT were set to 0.700 MeV and AP and PCUT were set to 0.010 MeV. No ESTEPE restriction was used for these calculations. For both cases the value of b_{min} was set to 5.428.

The absolute dose results were found to agree within 0.2% with dose uncertainties of between 0.6 and 1.7% (at 1σ). DRATIO was used to calculate the ratio of the response of the actual chamber to the response of the water equivalent chamber in each case. The dose ratios were found to agree within 0.2% with uncertainties on the dose ratios of between 0.2 - 2.1% (at 1σ). This agreement is sufficient to confirm that a dose calculation using a combination of PHSCHAM and DOSCHAM agrees with a dose calculation using DOSCHAM only.

2.2 Comparison with DOSRZPAR

The next method of validation compared the results for the response of a simplified cylindrical cavity chamber at depth in a cylindrical water phantom calculated using the new EGS4 user-codes PHSCHAM and DOSCHAM with the results calculated using the user-code DOSRZPAR. Absorbed dose calculations were performed for a cylindrical cavity chamber where all chamber materials are present and for a water equivalent chamber. The simulations were carried out with the chamber placed at a depth of 5 cm within a cylindrical water phantom in a monoenergetic beam of 4 MV X-rays. These calculations used identical transport parameters (see values given for previous validation case) and materials. As PHSCHAM and DOSCHAM calculate the response of the internal regions of a thimble shaped volume in a cubic phantom these simulations modelled the hemispherical material and the cubic phantom as water. This meant that the simulation geometry in both cases was the same. As PHSCHAM does not have an option to simulate a monoenergetic beam of X-rays incident on the front face of the phantom, a FORTRAN program was written which randomly picks points over the surface of the front face of a phantom and records the co-ordinates of these points in a file in a format which can be read in by PHSCHAM. The dose results were found to agree within 3% with dose uncertainties between 0.7% and 1.4% (at 1σ). DRATIO was used to calculate the ratio of the response of the chamber to the response of the water equivalent chamber for the DOSCHAM calculations. The dose ratios were found to agree within 0.4% where the uncertainties on the dose ratios were less than 1.5% (at 1σ).

2.3 Ratio of 2 MV air kerma to ^{60}Co absorbed dose calibration factors

The EGS4 user-code PHSCHAM has an option to allow the use of a point source at a specified distance from the front face of the phantom reading an energy spectrum from an input file. This input file needs to be in the form of a measured or calculated probability distribution. PHSCHAM was used with the point source option in order to calculate the 2 MV phase space spectrum on the surface of a chamber in an air phantom with a source to chamber distance of 180 cm. The simulations used an identical geometry to dose calculations described in Section 3.2 except that no Perspex sheath is required and a Delrin build-up cap is necessary in order to ensure charged particle equilibrium within the chamber. The calculated probability distribution for the 2 MV X-ray spectrum from the NPL Van

de Graaf facility was used to determine the full phase space spectrum incident on the surface of the chamber with build-up cap.

Two dose calculations with identical geometries were performed with the user-code DOSCHAM. The first calculation modelled all the materials of the ion chamber (plus build-up cap) in air. The second calculation was identical except that all the materials were replaced with air of the same density as the original material (i.e. an air equivalent chamber). By keeping the density of the air the same as the materials in the previous calculation many of the systematic errors that are present in the dose calculations are reduced when taking the dose ratio. Pairs of calculations used the same b_{min} value, of 3.19, in order that any systematic errors in the dose calculation are again reduced when taking the dose ratio. AE and ECUT were set to 0.521 MeV and AP and PCUT were set to 0.010 MeV for all regions in the geometry except for the air cavity inside the ion chamber. For this air cavity region, AE and ECUT were set to 0.516 MeV and AP and PCUT were set to 0.005 MeV.

DOSCHAM has an option to allow the primary dose, the primary dose excluding primary photon attenuation and the scattered dose to be scored separately as well as the total dose. For these calculations the ratio of the chamber response in 2 MV X-rays to the air kerma at the same point in the absence of the chamber (represented by an air equivalent chamber) is required. The wall of the air equivalent chamber is of a much greater density than normal air. This can be equated to a much larger volume of air being present between the source and the point of measurement that will attenuate and scatter the incident photons and electrons. Therefore in order to determine the response in the absence of the chamber the primary dose component excluding primary photon attenuation is used. As there is a high-density wall surrounding the air cavity in the air equivalent chamber there is charged particle equilibrium in this volume. Therefore the dose to the air cavity is equal to the collision kerma. To find the total air kerma a factor, g_{air}, needs to be applied to account for losses to bremsstrahlung radiation. This factor has a value of 0.997 for the 2 MV spectrum used.

DRATIO was used to calculate the ratio of the chamber response in 2 MV X-rays to the air kerma at the same point in the absence of the chamber (represented by an air equivalent chamber). The measured value for the stem scatter correction for the chamber in air was applied to the calculated ratio to give the air kerma calibration factor in 2 MV X-rays. The calculated ratio of 2 MV air kerma calibration to ^{60}Co absorbed dose calibration factor is 0.919 with an SEOM of 0.45% using the calculated absorbed dose factor for ^{60}Co determined in this work. The measured value for the ratio of the 2 MV air kerma calibration factor to ^{60}Co absorbed dose calibration factor is 0.913. Therefore the measured and calculated results agree within 2σ total random uncertainty.

Appendix 3: Material Specifications

The following is a list of all the materials used, their density and the percentage by weight of their constituents.

Material	Density (g/cc)	Constituent	Weight %
Aluminium	2.669	Al	100.0
Aluminium Alloy	2.669	Si	1.0
		Fe	0.5
		Cu	0.1
		Mn	0.3
		Mg	0.9
		Cr	0.2
		Zn	0.2
		Ti	0.1
		Al	96.7
Graphite	1.8	C	100.0
Amber	1.07	C	79.0
		H	10.5
		O	10.5
Air	1.205e-3	N	78.03
		O	21.03
		Ar	0.94
Water	1.0	H_2O	100.0
Perspex	1.19	$C_5H_8O_2$	100.0
Delrin	1.4	CH_2O	100.0

Table A.2: Material specifications for all materials used in the simulations