

**Evaluation of factors to convert absorbed
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Abstract. The National Physical Laboratory (NPL) provides a high-energy (4-19 MV) X-ray calibration service for secondary standard dosimeters in terms of absorbed dose to water. As the primary standard that is used for this calibration service is a graphite calorimeter absorbed dose calibrations must be converted from graphite to water. The conversion factors currently in use were determined prior to the commencement of this service. Since this time it has been identified that clinical LINACs have more inherent filtration than the NPL LINAC and so calibrations are now carried out for heavily filtered qualities. The conversion factors for heavily filtered qualities were determined by interpolation and extrapolation of lightly filtered results as a function of TPR (tissue phantom ratio). This work aims to evaluate these factors for all mega-voltage photon energies provided by the NPL LINAC for both lightly and heavily filtered qualities in two ways. The first method involves the use of the photon fluence scaling theorem. This states that if two blocks of different material are irradiated by the same photon beam, and if all dimensions are scaled in the inverse ratio of the electron densities of the two media, then, assuming that all photon interactions occur by Compton scatter the photon attenuation and scatter factors at corresponding scaled points of measurement in the phantom will be identical. The second method involves making in-phantom measurements of chamber response at a constant target-chamber distance. Monte Carlo techniques are then used to determine the corresponding dose to the medium in order to determine the chamber calibration factor directly. Values of the ratio of absorbed dose calibration factors in water to graphite determined in these two ways agreed with each other to within 0.2% (1σ uncertainty). The best fit to both sets of results agrees with values determined in previous work to within 0.4% (2σ uncertainty).

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Approved on behalf of Managing Director, NPL,
by M Sené, Head, Centre for Ionising Radiation Metrology

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1. Introduction

The high-energy (4-19 MV) X-ray calibration service in terms of absorbed dose to water that is provided at the NPL with the use of a linear accelerator (LINAC) uses a graphite calorimeter as its primary standard. The choice of material to be used in the construction of a calorimeter was considered by ICRU¹ and CCEMRI² who decided that the most suitable calorimeter material for use within medical dosimetry was graphite. The choice of graphite over water was made due to the properties of water that have made it an unsuitable choice in the past due to problems associated with the heat defect and its instability. Work is currently in progress at the NPL to overcome these problems with the design of a new water calorimeter³. At present, however, in order to provide a calibration for secondary standard dosimeter systems in terms of absorbed dose to water it is necessary to evaluate factors to convert absorbed dose calibrations from graphite to water for all energies provided by the calibration service.

The factors used to convert absorbed dose calibrations from graphite to water that are currently in use at the NPL were determined in previous work⁴ for all photon energies provided by the high-energy X-ray calibration service. However, subsequent to the completion of this work, it was identified that the NPL high-energy photon beam has much less inherent filtration in the beam than clinical LINACs. In order to match clinical beams more closely calibrations are presently carried out with additional filtration placed in the path of the beam. The additional filtration is provided by an extra thickness of aluminium where the thickness has been selected in order to match the NPL beam as closely as possible with a typical clinical beam by matching values of TPR. Previously determined conversion factors for lightly filtered qualities were used to generate values for heavily filtered qualities by interpolation and extrapolation against TPR.

This work has re-evaluated the conversion factors for all mega-voltage photon energies provided by the NPL LINAC using light filtration. These values were then compared with the previously experimentally determined values. The conversion factors have also been evaluated for all mega-voltage photon energies using heavy filtration and compared with the interpolated and extrapolated values that are currently in use. The factors that convert from absorbed dose to graphite to absorbed dose to water have been determined using two separate methods.

The first method (A) involves the use of the photon fluence scaling theorem which states, that if two blocks of different material are irradiated by the same photon beam and if all dimensions are scaled in the inverse ratio of the electron densities of the two media then, assuming that all photon interactions occur by Compton scatter, the photon attenuation and scatter factors at corresponding scaled points of measurement will be identical. This ensures that the proportions of scattered to primary radiation at scaled points of measurement in the two phantoms are the same. By assuming that the primary radiation obeys the inverse square law, the ratio of the primary photon fluences in the absence of the phantom medium can also be determined. Multiplying

the photon energy fluences by the photon mass-energy absorption coefficients for the media gives the ratio of doses, water to graphite, at the scaled points of measurement. Corrections are required for the effect of any departures from the scaling theorem assumptions, such as any deviation from the inverse square law due to air attenuation, and interactions that do not occur by Compton scatter, such as pair production and bremsstrahlung. The ratio of calibration factors, water to graphite, can then be found by taking the product of the ratio of doses, water to graphite, to the ratio of measured ionisations, graphite to water, at the scaled points of measurement.

The second method (B) involves making ionisation measurements at a constant target-chamber distance in the two phantoms. Monte Carlo methods can then be used to calculate the dose at the respective points of measurement in the two phantoms. The ratio of calibration factors in water and graphite can then be determined directly. No further corrections are required as this method does not rely on all interactions occurring solely by Compton scatter and measurements are carried out at the same target - chamber distance.

2. Method of Dose Ratios

2.1 General Overview

If an ionisation chamber placed in medium m is exposed to a photon beam then its absorbed dose calibration factor N_m is defined as: -

$$N_m = D_m / Q_m \quad (2.1)$$

where: -

D_m is the absorbed dose at a point in the undisturbed medium corresponding to the chamber reference point.

Q_m is the electric charge from ionisation in the chamber cavityⁱ.

Hence, the ratio of chamber calibration factors in water and graphite is: -

$$\frac{N_w}{N_c} = \frac{D_w / Q_w}{D_c / Q_c} = \frac{D_w}{D_c} \cdot \frac{Q_c}{Q_w} \quad (2.2)$$

The absorbed dose arising from photons of energy E is related to the photon energy fluence at a point in medium m irradiated by a photon beam under conditions of transient electron equilibrium by: -

i All ionisation measurements are corrected to standard atmospheric conditions (20°C, 101.325 kPa, 50% relative humidity) and to zero ion recombination.

$$\begin{aligned} D_m[E] &= \psi_m[E] \cdot (\mu_{tr}[E]/\rho)_m \cdot (1 - g_m[E]) \cdot \beta_m[E] \\ &= \psi_m[E] \cdot (\mu_{en}[E]/\rho)_m \cdot \beta_m[E] \end{aligned} \quad (2.3)$$

where, for photons of energy, E: -

$\psi_m[E]$ is the photon energy fluence at a point in the medium.

$(\mu_{tr}[E]/\rho)_m$ is the mass-energy transfer coefficient of the medium.

$g_m[E]$ is the fraction of initial kinetic energy of secondary electrons lost to bremsstrahlung in the medium.

$(\mu_{en}[E]/\rho)_m$ is the mass-energy absorption coefficient of the medium.

$\beta_m[E]$ is the ratio of absorbed dose to collision kerma at a point.

The photon beam generated by the NPL LINAC consists of a range of photon energies, therefore, in order to determine the total dose, the dose to the medium, $D_m[E]$, must be integrated over all energies of the spectrum.

The ratio of absorbed doses at given points in the two media for a photon energy spectrum with a maximum energy E_0 is therefore: -

$$\frac{D_w}{D_c} = \frac{\int_0^{E_0} dE \cdot \psi_w[E] \cdot (\mu_{en}[E]/\rho)_w \cdot \beta_w[E]}{\int_0^{E_0} dE \cdot \psi_c[E] \cdot (\mu_{en}[E]/\rho)_c \cdot \beta_c[E]} \quad (2.4)$$

and so: -

$$\frac{N_w}{N_c} = \frac{Q_c}{Q_w} \cdot \frac{\int_0^{E_0} dE \cdot \psi_w[E] \cdot (\mu_{en}[E]/\rho)_w \cdot \beta_w[E]}{\int_0^{E_0} dE \cdot \psi_c[E] \cdot (\mu_{en}[E]/\rho)_c \cdot \beta_c[E]} \quad (2.5)$$

The photon energy fluence at a point in a block of medium, m, will be determined by the incident photon energy fluence and its attenuation and the scattered radiation from the irradiated medium, i.e.: -

$$\psi_m = \psi_m^p + \psi_m^s \quad (2.6)$$

where: -

ψ_m^p is the primary photon energy fluence at a point in the medium.

ψ_m^s is the scattered photon energy fluence at a point in the medium.

The primary photon energy fluence for photons of energy E can also be expressed as: -

$$\psi_m^p[E] = {}_0\psi_m[E] \cdot (e^{-\mu[E]d})_m \quad (2.7)$$

where: -

${}_0\psi_m[E]$ is the photon energy fluence at the same point but in the absence of the medium.

$\mu_m[E]$ is the linear (narrow beam) attenuation coefficient of the medium for photons of energy E.

d_m is the depth of the given point in medium m along the path of the photons.

Therefore Equation 2.6 can also be written as: -

$$\psi_m[E] = {}_0\psi_m[E] \cdot (e^{-\mu[E]d})_m \cdot S_m[E] \quad (2.8)$$

where $S_m[E]$, the scatter factor for photons of energy E at a point in medium m, is given by: -

$$S_m[E] = 1 + \frac{\psi_m^s[E]}{\psi_m^p[E]} \quad (2.9)$$

This can also be written as: -

$$S_m[E] = 1 + \frac{\psi_m^s[E]}{(e^{-\mu[E]d})_m \cdot {}_0\psi_m[E]} \quad (2.10)$$

Therefore by combining Equations 2.5 and 2.8 this gives: -

$$\frac{N_w}{N_c} = \frac{Q_c}{Q_w} \cdot \frac{\int_0^{E_0} dE \cdot {}_0\psi_w[E] \cdot (e^{-\mu[E]d})_w \cdot S_w[E] \cdot (\mu_{en}[E]/\rho)_w \cdot \beta_w[E]}{\int_0^{E_0} dE \cdot {}_0\psi_c[E] \cdot (e^{-\mu[E]d})_c \cdot S_c[E] \cdot (\mu_{en}[E]/\rho)_c \cdot \beta_c[E]} \quad (2.11)$$

2.2 Set Up for Method A

2.2.1 Introduction

In the two set ups given in Figures 2.1.a and 2.1.b chambers are placed at depth in phantoms made of graphite and water where dA is the area of the front face of the chamber. The respective depths in graphite and water and the source to chamber distances are scaled by the inverse ratio of the electron densities of the phantom material. The source is assumed to be a collimated point source.

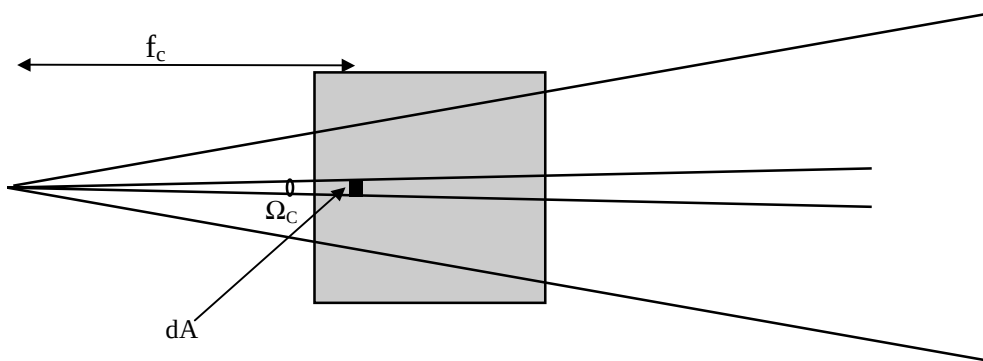


Figure 2.1.a Measurements in Graphite

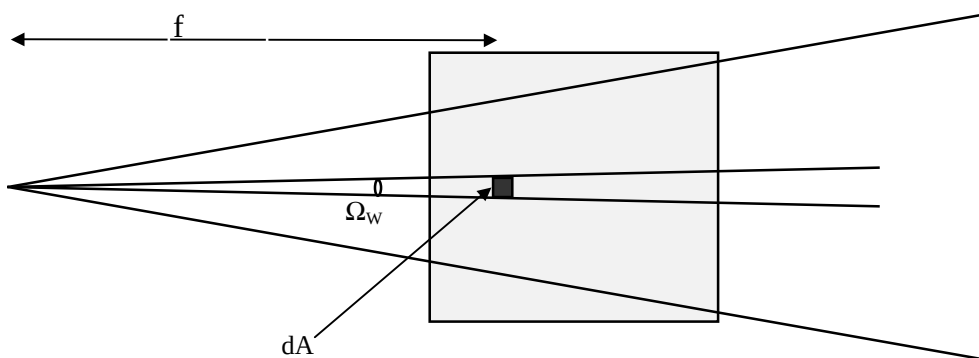


Figure 2.1.b Measurements in Water

The probability of a photon reaching the point of measurement must, therefore, be considered in three separate stages: the probability that the photon will initially be travelling in the right direction to reach the chamber, the probability of the photon not interacting in the phantom medium prior to reaching the chamber, and the probability of scattered radiation reaching the chamber.

2.2.2 Inverse Square Law

For an isotropic source, the fraction of radiation that is initially travelling towards the chamber in each situation is given by the solid angle subtended by the chamber over 4π .

The solid angle subtended by the (small) chamber at depth in the medium, Ω_m , is given by: -

$$\Omega_m = \frac{1}{f_m^2} \cdot dA \quad (2.12)$$

where: -

f_m is the distance from the source to the chamber in medium m.

dA is the area of the front face of the chamber.

The NPL LINAC source is in reality a collimated diverging beam rather than an isotropic source, however, when considering ratios of fluences this is not important. Therefore the photon energy fluences in the absence of the medium at the point in space corresponding to the given point in the medium for water and graphite are given by: -

$${}_0\Psi_w[E] = a[E] \frac{1}{f_w^2} \quad \text{and} \quad {}_0\Psi_c[E] = a[E] \frac{1}{f_c^2} \quad (2.13, 14)$$

where $a[E]$ is the primary fluence at unit distance from the point source, i.e. it is the same function of energy in each case.

Therefore Equation 2.11 can be expressed as: -

$$\frac{N_w}{N_c} = \frac{Q_c}{Q_w} \cdot \frac{f_c^2}{f_w^2} \cdot \frac{\int_0^{E_0} dE \cdot a[E] \cdot (e^{-\mu[E]d})_w \cdot S_w[E] \cdot (\mu_{en}[E]/\rho)_w \cdot \beta_w[E]}{\int_0^{E_0} dE \cdot a[E] \cdot (e^{-\mu[E]d})_c \cdot S_c[E] \cdot (\mu_{en}[E]/\rho)_c \cdot \beta_c[E]} \quad (2.15)$$

2.2.3 Photon Fluence Scaling Theorem

Only a fraction of the radiation initially travelling towards the chamber will reach the chamber as the radiation will be attenuated by the medium before reaching this point. If all interactions that occur in the medium are due to Compton scatter, the probability of interaction along a path of length d is proportional to the number of electrons per unit area, i.e. $\sigma \cdot d$ where σ is the electron density (number per unit volume) in the medium. Therefore by ensuring that there are equal numbers of electrons in the path of the incident radiation in the two media there will also be equal probability of the

radiation interacting (i.e. $\sigma_w d_w = \sigma_c d_c$). Therefore the primary attenuation in each medium is the same, i.e.: -

$$\left(e^{-\mu[E]d}\right)_w = \left(e^{-\mu[E]d}\right)_c \quad (2.16)$$

It is next necessary to consider the ratio of the proportion of scattered fluence at scaled points in the media. Figures 2.2.a and 2.2.b show two different media where the electron density of medium 1 is $2/3$ that of medium 2. The depth of the point of measurement in medium 1 has therefore been scaled by $3/2$ to the depth of the point of measurement in medium 2. An example of how a photon may interact via Compton scatter is shown for medium 1 in 2-D (electron paths are not shown). The path of this photon has then been shown for exactly the same interactions had they occurred in medium 2. The interactions that produce scattered radiation occur with equal probability in the two media, and so the number and energy of scattered photons match. It can be seen, therefore, that at the scaled points of measurement the same ratio of scattered fluence to primary photon fluence in the absence of the medium will be observed. It is also evident that in order for the same proportion of photons to reach the point of measurement the diameter of the beam of photons on the front face of the two media must also be scaled by the inverse ratio of the electron densities. This is achieved by scaling the distance from a point source in a collimated, diverging beam.

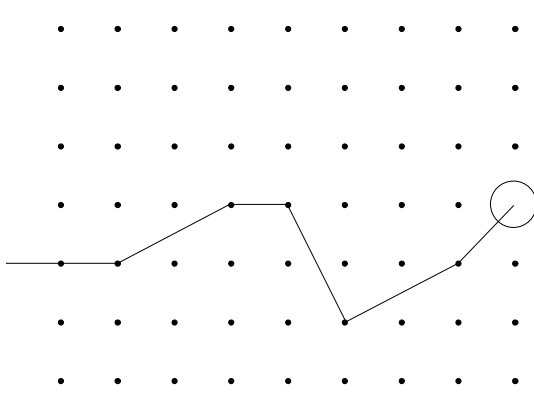


Figure 2.2.a: Example of scatter in medium 1

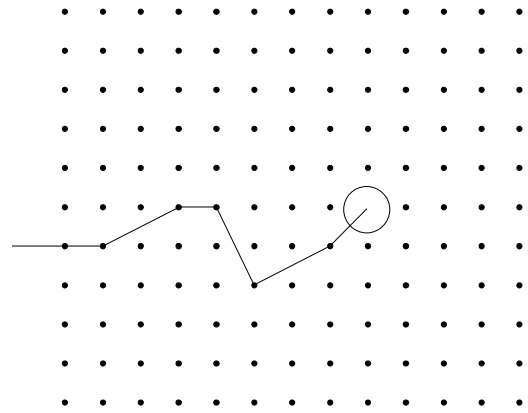


Figure 2.2.b: Example of scatter in medium 2

Therefore: -

$$\frac{\psi_w^s[E]}{\psi_w^0[E]} = \frac{\psi_c^s[E]}{\psi_c^0[E]} \quad (2.17)$$

and so from Equation 2.10: -

$$S_w[E] = S_c[E] \quad (2.18)$$

The scaling assumptions for Equations 2.16 and 2.18 are that they are both common functions of energy. Therefore a weighting factor, $w[E]$, which is common to both numerator and denominator of Equation 2.15 can be defined by: -

$$w[E] = a[E]e^{-\mu[E]d}S[E] \quad (2.19)$$

and so Equation 2.15 can be simplified to: -

$$\frac{N_w}{N_c} = \frac{Q_c}{Q_w} \cdot \frac{f_c^2 \int_0^{E_0} dE \cdot w[E] \cdot (\mu_{en}[E]/\rho)_w \cdot \beta_w[E]}{f_w^2 \int_0^{E_0} dE \cdot w[E] \cdot (\mu_{en}[E]/\rho)_c \cdot \beta_c[E]} \quad (2.20)$$

Equation 2.20 is the key equation to be used in Method A in the determination of the ratio of the absorbed dose calibration factors in water to graphite.

2.2.4 Experimental Set up

For this method that uses the photon fluence scaling theorem it was necessary to scale all dimensions by the inverse ratio of the electron densities. The scaled lengths for two media are given by the following equation: -

$$\frac{L_{m1}}{L_{m2}} = \frac{\sigma_{m2}}{\sigma_{m1}} \cdot \frac{\rho_{m2}}{\rho_{m1}} \quad (2.21)$$

where: -

L_{m1} and L_{m2} are the scaled distances in media 1 and 2.

σ_{m1} and σ_{m2} are the electron densities of media 1 and 2 (electrons/unit mass).

ρ_{m1} and ρ_{m2} are the mass densities of media 1 and 2.

The graphite and water phantoms used for these measurements were built prior to the commencement of the high-energy absorbed dose calibration service. The water phantom is a cube of side 26.4 cm with Perspex ($C_5H_8O_2$) walls that are 0.962 cm thick. The phantom has various slots where a jig can be positioned which can hold a waterproof Perspex sleeve designed for use with a thimble ionisation chamber. The slot in which the jig was placed for these measurements was designed to position the chamber at the appropriate ICRU recommended depth at which calibrations should be carried out in X-radiation¹. This states that measurements should be carried out at an effective depth in water of 5 cm for photon energies up to 11 MV and at an effective depth in water of 7 cm for photon energies above 11 MV. The depth in water is calculated by assuming that the 0.962 cm thick Perspex wall with a mass density of 1.18 gcm^{-3} has an effective thickness of 1.105 cm of water based on matching electron densities. The density of water at 20°C was assumed to be 0.9982 gcm^{-3} . For

measurements at energies up to 11 MV the graphite phantom is a cube that is made up of 4 separate blocks (numbered 13, 19, 20 and 21) that are bolted together. For measurements at energies above 11 MV block 4 is placed in front of block 13 in order to provide the required extra build-up. A plan along the length of the graphite phantom with dimensions is shown in Figure 2.3 and the measured densities are given in Table 2.1. The line AB marks the position of the centre of the chamber.

The graphite and water phantoms were originally designed for measurements using scaled electron densities in this way so their scaled measurement depths are already closely matched, although not exactly. In the previous work corrections were applied for the non-exact scaling of the depth of measurement in the graphite phantom. All dimensions for the graphite phantom are fixed, however, it was possible to adjust the depth in water by applying pressure to the jig that held the Perspex sleeve in place in the water phantom. By ensuring that the depths were exactly scaled it was not necessary to apply corrections to correct for the effect of the Perspex front wall and the effect of non-exact scaling of the respective measurement depths in the water and graphite phantoms.

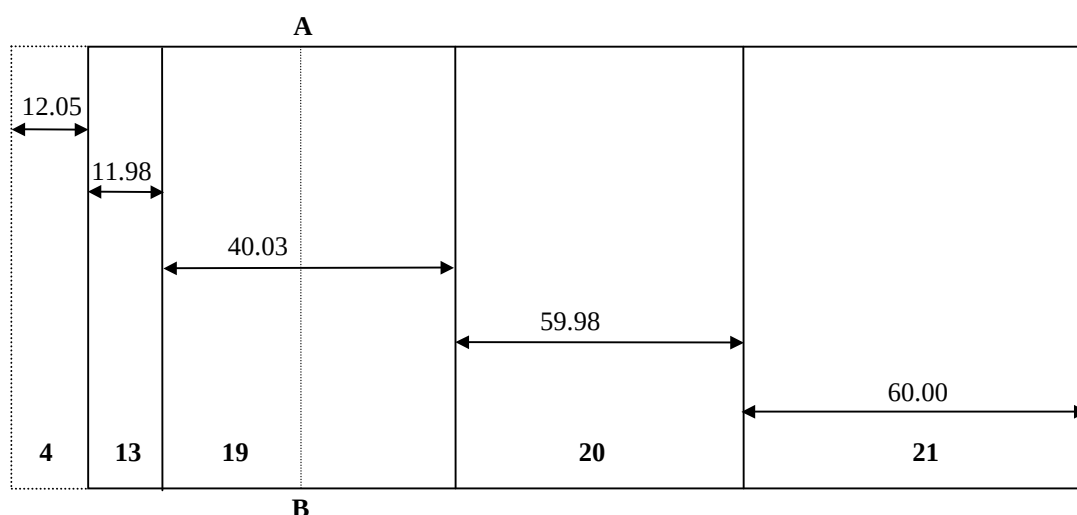


Figure 2.3: Side Plan of Graphite Phantom (all dimensions in mm).

Identity number	Purpose	Density gcm^{-3}	Thickness	
			mm	gcm^{-2}
4	high-energy	1.754	12.05	2.1136
13	build-up	1.755	11.98	2.1025
19	chamber insert	1.749	40.03	7.0012
20	backscatter	1.755	59.98	10.53
21	backscatter	1.771	60.00	10.63

Table 2.1: Measured Densities of Blocks of Graphite Phantom

From the dimensions and densities given it can be seen that the actual depth of the effective point of measurement in the graphite phantom is 5.603 gcm^{-2} for energies up to 11 MV and 7.717 gcm^{-2} for energies above 11 MV. The following method was used to determine the required depth in water for exact scaling of the depths of measurement in the graphite and water phantoms.

σ_m , the number of electrons in 1 g of material, m, is given by: -

$$\sigma_m = \frac{\epsilon}{A_r} N_0 \quad (2.22)$$

where: -

ϵ is the number of electrons per atom of material m.

A_r is the relative atomic mass of material m.

N_0 is the Avogadro number (atoms/gram-atomic mass).

Therefore, we know that: -

$$\sigma_p, \text{ the number of electrons in 1 g of Perspex} = \frac{54}{100} N_0$$

$$\sigma_c, \text{ the number of electrons in 1 g of graphite} = \frac{6}{12} N_0$$

$$\sigma_w, \text{ the number of electrons in 1 g of water} = \frac{10}{18} N_0$$

In order to scale dimensions of Perspex and graphite Equation 2.21 becomes: -

$$\frac{L_p}{L_c} = \frac{\sigma_c}{\sigma_p} \cdot \frac{\rho_c}{\rho_p}$$

And so the thickness of graphite that is equivalent to the thickness of the Perspex front face of the water phantom (0.962 cm thick with a density of 1.18 gcm^{-3}) is given by: -

$$L_c = L_p \frac{\rho_p}{\rho_c} \cdot \frac{\sigma_p}{\sigma_c} = 0.962 \times \frac{1.18}{1.75} \times \frac{54/100}{6/12} = 0.701 \text{ cm}$$

For energies up to 11 MV the total thickness of graphite in front of the centre of the chamber is:

$$(2.1025 + 3.5006) \text{ gcm}^{-2} = 5.603 \text{ gcm}^{-2}$$

Therefore for equivalent scaling there must be a thickness of water that is equivalent to: -

$$[5.6031 - (0.70056 \times 1.75)] \text{ gcm}^{-2} = 4.377 \text{ gcm}^{-2}$$

And so the depth of water that is equivalent to 4.377 gcm^{-2} is given by: -

$$L_w = L_c \frac{\rho_c}{\rho_w} \cdot \frac{\sigma_c}{\sigma_w} = 4.3371 \times \frac{1}{0.9982} \times \frac{6/12}{10/18} = 3.95 \text{ cm of water}$$

The same method can be used to show that for energies above 11 MV the chamber must be placed at a depth in water of 5.85 cm from the inside of the Perspex front face of the water phantom for equivalent scaling.

At the start and end of the series of measurements carried out for this work careful metrology ensured that the chamber was positioned at these depths from the inside face of the water phantom. Small changes of the order 1 mm were observed between the start and the end of the measurements. This contribution to the uncertainty will be small in comparison to other measurement uncertainties, discussed more fully in Section 4, and is therefore ignored.

The dimensions of the cross-sections of the water and graphite phantoms were not exactly scaled. However, by making all measurements with the beam entirely enclosed by the respective phantom the effect was assumed to be negligible. A few measurements were carried out with the beam larger than the front face of the phantom that showed a measurable effect. High-energy X-ray calibrations carried out at the NPL use a fixed collimator that will be called the large collimator for this report. Measurements were also made using a second fixed collimator that will be called the small collimator. The small collimator was used in order that measurements could be made at longer target to chamber distances whilst still restricting the size of the beam to be entirely enclosed by the phantom.

The amount of backscatter material provided by the phantom medium behind the point of measurement was also not exactly scaled. The method shown above for scaling the depths of the point of measurement in phantom was used to determine the difference between the amount of graphite backscatter required for exact scaling with the water phantom and the actual amount of graphite backscatter for these measurements. The difference was found to be 0.6 gcm^{-2} for energies up to 11 MV and 4 gcm^{-2} for energies above 11 MV. Previous measurements⁴ in the Co-60 beam showed that on removing Block 21, with a thickness of 10.63 gcm^{-2} , the dose at the point of measurement changed by only 0.25%. This effect would decrease with increasing energies on the linear accelerator. The ratio of primary to total dose at the point of measurement in the graphite phantom was determined using Monte Carlo techniques for exact scaling with the water phantom and for the measurement set up used in this work for energies above 11 MV. For a 12 MV X-ray beam for both light and heavy filtration no difference in the primary to total dose ratio was observed within the quoted random uncertainties that were of the order $\pm 0.02\%$. It was therefore concluded that the effect on measurements made in this work of non-exact scaling of the backscatter material would be negligible.

2.2.5 Virtual Source Correction

The photon fluence scaling theorem relies on the assumption that, for a particular photon beam, the inverse square law applies. In the previous work it was ascertained that measurements made on the NPL LINAC, once corrected for air attenuation, did obey the inverse square law. This is due to the construction of the collimator that has been designed to focus very close to the small focus spot and to minimise penumbra and collimator scatter. It was, however, identified that the best agreement with the inverse square law for this work was obtained using a virtual source of X-radiation which could lie between a couple of centimetres behind the target up to a few millimetres in front of the target. No pattern was observed in the position of the virtual source with energy, filtration or collimator size. Measurements made at 10 MV were, however, repeated with the target moved an additional 2 cm out from the end of the flight tube. The position of the virtual source was seen to follow the position of the target. It was therefore concluded that collimator scatter that would bring the virtual source in front of the target and would be independent of the target position could not cause the observed difference in the position of the real and virtual source.

In order to determine the position of the virtual source for this work it was assumed that as the primary component of the photon fluence obeys the inverse square law the chamber response to the primary photon fluence would vary in the same way. Chamber response measurements were made at the beginning of each day's set of measurements with a NE2561 chamber placed at depth in a water phantom at varying source to chamber distances with either the large or small collimator. Measurements were made using the water phantom instead of the graphite phantom due to its' larger dimensions which allowed measurements to be made at greater target to chamber distances.

The total ionisation collected by the chamber is a sum of the part due to primary and the remainder due to scattered photon fluence. It was therefore necessary to correct measurements of the total charge collected to give the chamber response to the primary contribution. This was done using factors determined using Monte Carlo techniques. The EGS4 code DOSRZPAR (see Section 3.3) was used to calculate the primary and total dose components at various target to chamber distances in a water phantom. The ratio of primary to total dose was then used to correct measurements of total collected charge to give the chamber response to the primary component. The Monte Carlo calculations determined dose ratios rather than charge ratios and so it was necessary to assume that the chamber response (charge/dose) is the same for primary and scattered radiation. This approximation introduces an uncertainty that is considered negligible in comparison to the random uncertainties in the Monte Carlo simulations.

After correcting also for air attenuation, see Section 2.2.6, the chamber response in water to the primary fluence, $Q'_{p,w}$, should obey the inverse square law. Any deviation from the inverse square law was assumed to be due to a displacement of the virtual

source of X-radiation from the centre of the target. SigmaPlotⁱⁱ was used to plot $Q'_{p,w} \cdot (f_w + y)^2$ against f_w , where f_w is the target to chamber distance, for various values of y , the distance of the virtual source behind the target. The optimal value of y was that which produced the smallest gradient. Figure 2.4 shows such an example where $y = 0.2$ cm was selected as giving the smallest gradient.

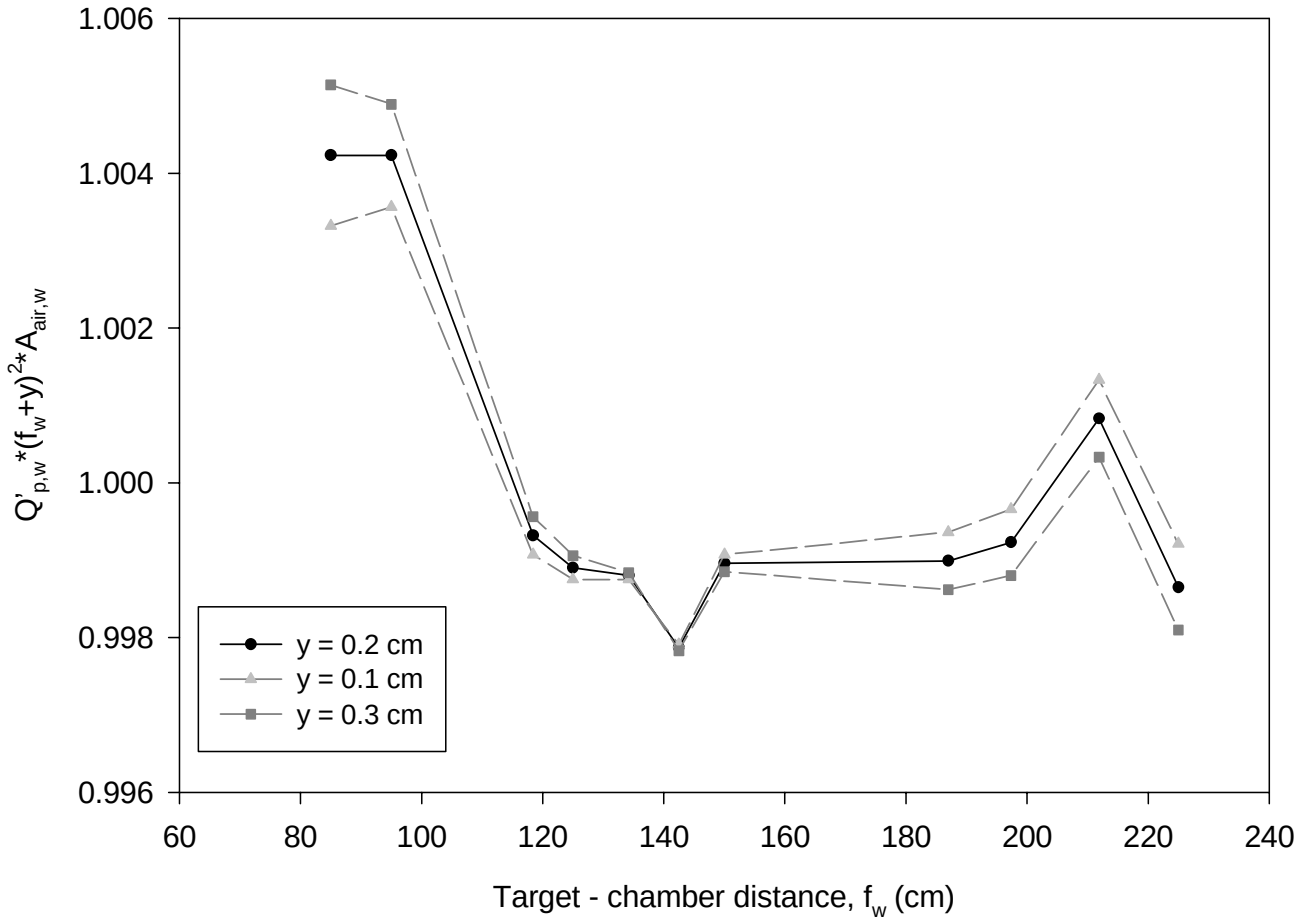


Figure 2.4: A Plot of $Q'_{p,w} \cdot (f_w + y)^2$ against f_w for 4 MV heavy filtration - large collimator

The virtual source correction that is needed to correct values of $(f_c/f_w)^2$ is therefore given by: -

$$F(1) = \frac{(f_c + y)^2}{(f_w + y)^2} \cdot \frac{(f_w)^2}{(f_c)^2} \quad (2.23)$$

ii SigmaPlot for Windows, Version 4.01

Values of the virtual source correction were determined for small and large collimator set ups for both lightly and heavily filtered qualities. It was found that for lightly filtered qualities at all energies there was a noticeable decrease in the measured chamber to monitor charge ratio close to the collimator. One explanation could be backscatter from the water phantom causing an increase in the charge collected in the monitor chamber. When determining the virtual source correction measurements made at a focal distance of less than 95 cm were not used in determining the smallest gradient

It was also found that for heavily filtered qualities there was a noticeable increase in the measured chamber to monitor charge ratio close in to the collimator. This can be explained by radiation, scattered in the collimator and/or the additional filtration, reaching the chamber at measurement distances close to the collimator. When determining the virtual source correction measurements made at a focal distance of less than 125 cm for energies up to 8 MV and less than 118.4 cm for energies above 8 MV were not used in determining the smallest gradient

2.2.6 Air Attenuation Correction

Measurements made for Method A rely on the unattenuated photon energy fluence, ${}_0\Psi_m[E]$, varying inversely as the square of the target to point of measurement distance, f_m . Therefore, the ratio of the unattenuated photon energy fluences at the scaled points of measurement in the absence of the medium for water to graphite is given by combining Equations 2.13 and 2.14: -

$$\frac{{}_0\Psi_w[E]}{{}_0\Psi_c[E]} = \frac{f_c^2}{f_w^2} \quad (2.24)$$

As measurements are made at different target to chamber distances it is necessary to apply a correction for the different amount of attenuation of the photon energy fluence in air. The photon fluence was determined using Monte Carlo techniques at a defined scoring plane at 70 cm from the target, see Section 3.2, and this fluence was ‘binned’ into 200 energy bins. This was used to determine the photon energy fluence at the scoring plane, $\Psi_{sp}[E]$. Narrow beam attenuation coefficients for air taken from Reference 5 were applied to the photon energy fluence at the scoring plane to give the photon energy fluence at the front face of the phantom: -

$$\Psi_{ff,m}[E] = \Psi_{sp}[E] \exp(-\mu_{air}[E]t_{sp,m}) \quad (2.25)$$

where: -

$\Psi_{sp}[E]$ is the photon energy fluence at the defined scoring plane.

$\mu_{air}[E]$ is the linear (narrow) beam attenuation coefficient of air for photons of energy E.

$t_{sp,m}$ is the thickness of air from the scoring plane to the front face of the phantom of material m.

The effective value of the attenuation correction of the air between the scoring plane and the phantom of material, m, is given by: -

$$A_{air,m} = \frac{\int_0^{E_0} dE \cdot \psi_{ff,m}[E]}{\int_0^{E_0} dE \cdot \psi_{sp}[E]} \quad (2.26)$$

And so the air attenuation correction that is required to correct values of $(f_c/f_w)^2$ is given by: -

$$F(2) = A_{air,w} / A_{air,c} \quad (2.27)$$

2.2.7 Correction for Pair Production

The photon fluence scaling theorem relies on all dimensions in corresponding set ups being scaled by the inverse ratio of the electron densities of the two phantom media. It also assumes that the only interaction occurring is by Compton scatter that is linearly dependent on the electron density of the medium. This ensures that the primary photon energy fluence and the proportion of scattered to primary photon fluence at corresponding scaled depths in the two media is the same. In comparison bremsstrahlung and pair production which are directly proportional to Z^2 (the square of the atomic number) instead of Z do not obey the photon fluence scaling theorem as their differential effect in two phantoms scaled by electron density does not cancel out. It is therefore necessary to apply a correction to account for these processes.

Firstly, it is necessary to determine a correction to account for the different proportion of the primary photon fluence that is scattered out of the beam due to pair production in the two phantoms. This correction can be determined by considering the exponential narrow-beam attenuation of the photons that includes attenuation due to pair production.

In order to determine the necessary correction the photon energy fluence was determined at a defined scoring plane as described previously in Section 2.2.6. Values of the narrow beam attenuation coefficients for air, water and graphite were interpolated from values given in Reference 5 to give values of the coefficients for the mid-point energies of each bin. The correction for narrow beam attenuation of the beam in air was applied to the photon energy fluence from the scoring plane to the

front face of the corresponding phantom. The corrected photon energy fluence at the front face of the phantom, $\psi_{ff,m}[E]$, is therefore given by Equation 2.25.

For each set up the correction for narrow beam attenuation of the beam from the front face of the phantom to the scaled point of measurement in the corresponding medium was applied to this corrected photon energy fluence. And so the photon energy fluence at the scaled depth of measurement in the phantom of medium m is given by: -

$$\psi_{pt,m}[E] = \psi_{ff,m}[E] \exp(-\mu_m[E]d_m) \quad (2.28)$$

where: -

$\mu_m[E]$ is the linear (narrow) beam attenuation coefficient of the medium for photons of energy E .

d_m is the depth of the point of measurement in the phantom.

Therefore the effective attenuation factor of the medium that includes attenuation due to pair production is given by: -

$$A_{pp,m} = \frac{\int_0^{E_0} dE \cdot \psi_{pt,m}[E]}{\int_0^{E_0} dE \cdot \psi_{ff,m}[E]} \quad (2.29)$$

and so the correction factor which needs to be applied to values of $(f_c/f_w)^2$ to account for attenuation in the water and graphite phantoms due to pair production is given by:-

$$F(3) = \frac{A_{pp,w}}{A_{pp,c}} \quad (2.30)$$

2.2.8 Correction for Bremsstrahlung and Annihilation Radiation

In order for the photon fluence scaling theorem to be valid it is required that photons incident on corresponding scaled points have the same energy spectrum in both phantoms. However, the intensity and spectrum of radiation due to bremsstrahlung and annihilation will differ in the two media, and means that a further correction, $F(4)$, to the scaling theorem is required.

Pair production involves the creation of an electron and positron and absorption of the photon. The positron will then annihilate with another electron, normally close to the point at which it was created, producing two photons of equal energy travelling in opposite directions. These photons add to the scattered radiation reaching the point of

measurement. Photons that undergo Compton scatter knock out an electron from the electron shell surrounding each atom in the medium. This electron may then create bremsstrahlung radiation that is released when any charged particle decelerates as may happen when an electron is scattered by the charged nucleus of an atom. This bremsstrahlung radiation will also add to the scattered radiation reaching the point of measurement.

In the previous work it was determined that this effect is ‘not as serious as might be imagined’. The reasoning was that the X-ray spectrum from the NPL LINAC is strongly skewed towards lower energies (e.g. mean photon energy of 10 MV beam is 3 MeV). Also, as water and graphite are both low atomic number materials, the proportion of bremsstrahlung and pair production should be similar and so should tend to cancel out when taking ratios.

However, it remains to estimate a correction to apply to the ratio of scatter factors to correct for these effects. The Monte Carlo code DOSRZPAR was modified so that the dose due to Compton and Rayleigh scattered photons could be scored separately to the dose due to bremsstrahlung and the dose due to annihilation photons. Simulations were carried out as described in Section 3.3 for pairs of scaled distances.

By combining Equations 2.3 and 2.9 the scatter factor at a point in the undisturbed medium, m , corresponding to the chamber reference point, S_m , can be expressed as: -

$$S_m = 1 + \frac{\int_0^{E_0} dE \cdot D_m^s[E] \cdot (\mu_{en}[E]/\rho)_m^p \cdot \beta_m^p[E]}{\int_0^{E_0} dE \cdot D_m^p[E] \cdot (\mu_{en}[E]/\rho)_m^s \cdot \beta_m^s[E]} \quad (2.31)$$

where: -

$D_m^s[E]$ is the contribution to the absorbed dose from the scattered photon fluence.

$D_m^p[E]$ is the contribution to the absorbed dose from the primary photon fluence.

$(\mu_{en}[E]/\rho)_m^p$ is the mass-energy absorption coefficient of the medium for the primary photon energy fluence.

$(\mu_{en}[E]/\rho)_m^s$ is the mass-energy absorption coefficient of the medium for the scattered photon energy fluence.

$\beta_m^p[E]$ is the ratio of absorbed dose to collision kerma at a point for the primary photon energy fluence.

$\beta_m^s[E]$ is the ratio of absorbed dose to collision kerma at a point for the scattered photon energy fluence.

Since the calculated absorbed dose values are due to the primary or scattered contributions of the photon energy fluence summed over all energies, it was necessary to determine average values of the mass-energy absorption coefficients and the correction for centre of electron production. The primary and scattered photon energy fluences at the scaled measurement points in water and graphite are not well known, therefore, estimates of the average energy of the primary and scattered components of the mega-voltage photon beams were made. These estimates were used to determine approximate values of the average mass-energy absorption coefficients and the correction for centre of electron production in water and graphite for the two components.

Values of the mass-energy absorption coefficient were taken from Reference 5 and values of the correction for centre of electron production were determined as described in Section 2.2.10. An estimate of the ratio of scatter factors could then be determined for when the dose due to bremsstrahlung and pair production processes is included and when it is excluded.

The correction, $F(4)$, is therefore given by:-

$$F(4) = \frac{(S_w/S_c)_{\text{incl br + an}}}{(S_w/S_c)_{\text{excl br + an}}} \quad (2.32)$$

It was found that the correction, $F(4)$, at 4 MV with light filtration was +0.01%, at 12 MV with heavy filtration was +0.04% and at 19 MV with heavy filtration was +0.05%. The uncertainties associated with these corrections were of the same order of magnitude as the correction. It was concluded, therefore, that no correction would be applied to account for bremsstrahlung and annihilation radiation and instead the overall uncertainty on Method A would be increased to allow for this.

2.2.9 Determination of the Ratio of Mass-Energy Absorption Coefficients

For this work, values of the photon mass-energy absorption coefficients ($\mu_{\text{en}}[E]/\rho$) for water and graphite were required at the point of measurement in the respective phantoms. The value of ($\mu_{\text{en}}[E]/\rho$) is energy dependent and so values for the photon spectra of interest were determined by taking a weighted average over the photon energy fluence. It was therefore necessary to determine the photon energy fluence at depth in the phantom as described in Section 2.2.7. The photon energy fluence at the point of measurement in the phantom, $\psi_{\text{pt,m}}[E]$, is therefore given by Equation 2.28.

The weighted average over the photon energy fluence of the photon mass-energy absorption coefficient at the point of measurement in the phantom of material m is therefore given by: -

$$\int_0^{E_0} dE (\mu_{en}[E]/\rho)_m = \frac{\int_0^{E_0} dE \cdot w[E] \cdot \psi_{pt,m}[E] \cdot (\mu_{en}[E]/\rho)_m \cdot \beta[E]_m}{\int_0^{E_0} dE \cdot w[E] \cdot \psi_{pt,m}[E] \cdot \beta[E]_m} \quad (2.33)$$

The values of $(\mu_{en}[E]/\rho)$ for water and graphite were obtained by interpolating the tabulated data of Hubbell⁵ to give the value at the mid-point of each energy bin.

2.2.10 Correction for Centre of Electron Production

This section will consider the relationship of dose, D_m , to collision kerma, $K_{c,m}$, in a slab of material, m , with a broad parallel beam of high-energy photons, free of electron contamination, perpendicularly incident on it. It has shown that at depths greater than the maximum electron range, R , a condition called transient charged particle equilibrium exists which means that the ratio of D_m to $K_{c,m}$ reaches a fixed value (which is greater than unity). Kase et al⁶ define a mean distance $\bar{x}$ that the secondary electrons carry kinetic energy “downstream” before depositing it as absorbed dose. The value of $\bar{x}$, see Figure 2.5, is given by the horizontal separation of curves D_m and $K_{c,m}$ anywhere past the build-up.

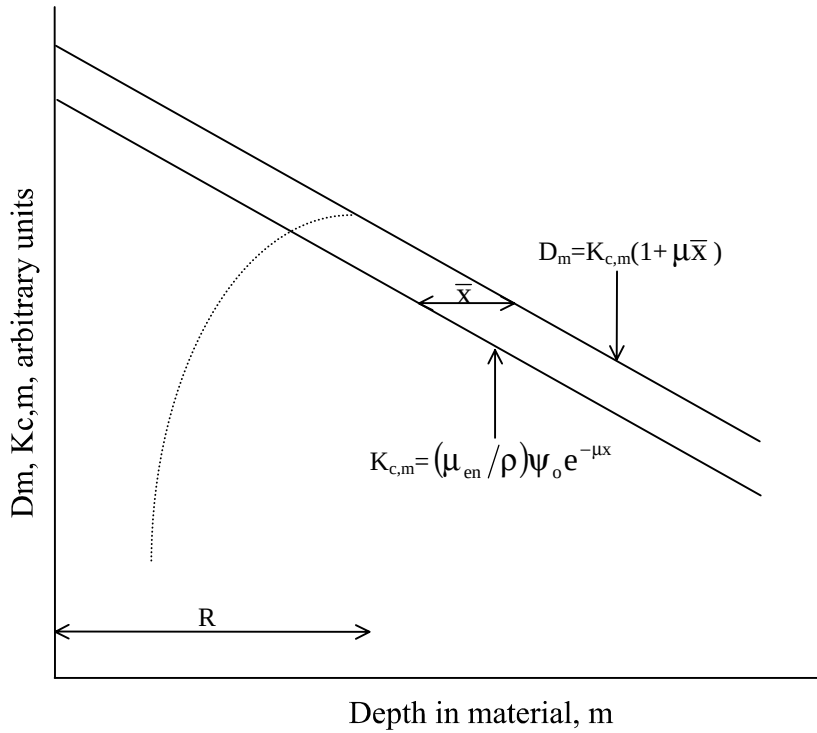


Figure 2.5: Collision kerma, $K_{c,m}$, and absorbed dose, D_m , as a function of depth along the central axis of a slab of material irradiated with photons

In order to determine the necessary correction for centre of electron production the photon energy fluence at depth in water and graphite phantoms was obtained as described previously in Section 2.2.7. Values of $\bar{x}$ for water and graphite were interpolated from the data given in Reference 7 to give values for the mid-point energies of each bin and a weighted average over the photon energy fluence was determined for water and graphite.

These values for $\bar{x}$ were used to give the ratio of D_m to $K_{c,m}$ as shown by: -

$$\frac{D_m[E]}{K_{c,m}[E]} \cong 1 + \mu'[E]\bar{x}[E] \quad (2.34)$$

This gave the required correction for the centre of electron correction: -

$$\frac{\beta_w[E]}{\beta_c[E]} = \frac{\left(\frac{D[E]}{K_c[E]}\right)_w}{\left(\frac{D[E]}{K_c[E]}\right)_c} \quad (2.35)$$

2.3 Set Up for Method B

In the two set ups given in Figures 2.6.a and 2.6.b chambers are placed at depth in phantoms made of graphite and water. The respective depths in graphite and water are scaled by the inverse ratio of the electron densities of the phantom material. The source to chamber distance is fixed for both cases and the source is assumed to be a collimated point source.

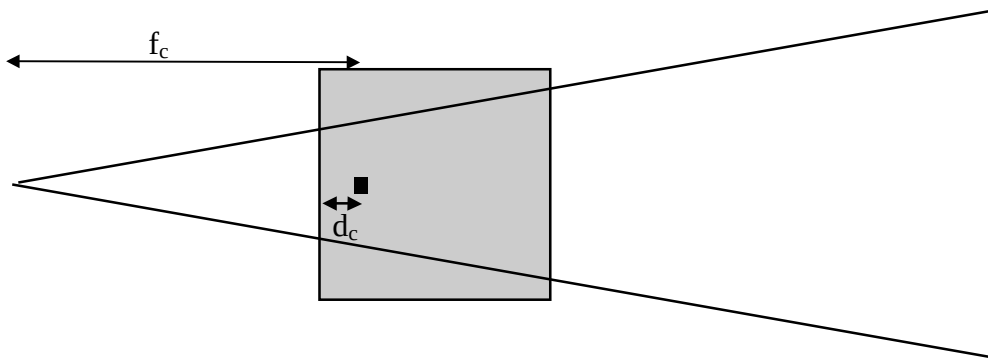


Figure 2.6.a Measurements in Graphite

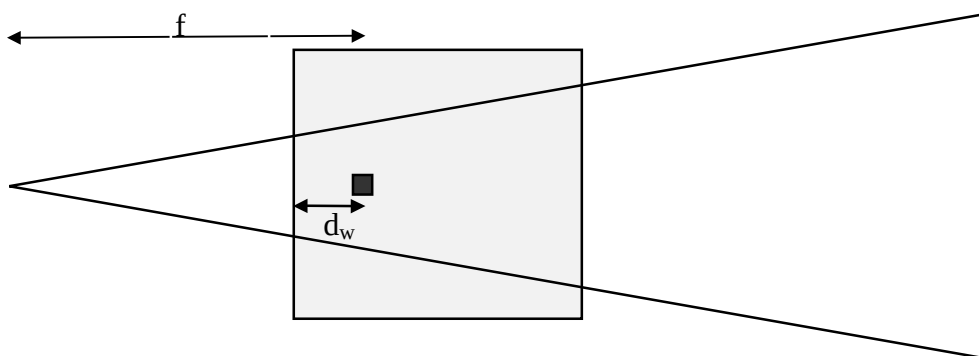


Figure 2.6.b Measurements in Water

The set up for method B is the same as for method A except that in method B the target to chamber distance is kept the same for each set of measurements in graphite and water. The charge collected was measured in each case and the corresponding dose to the point in the undisturbed medium corresponding to the centre of the chamber was determined using Monte Carlo methods, see Section 3.3. The dose ratio was calculated for various target to chamber distances and no trend with distance was observed. Therefore, for all energies for both light and heavy filtration, only one pair of simulations was carried out. And so the ratio of calibration factors in water and graphite could be determined using Equation 2.2.

The advantage of using this method was that it was not necessary to apply any corrections as D_m and Q_m could both be determined directly. Also by taking ratios of doses the non-random uncertainty associated with approximations in the Monte Carlo method is reduced. The NPL LINAC simulation does not include the effects of the electron beam being focused on the target. For this reason the intrinsic angular divergence of the beam is not necessarily well modelled, and so in particular, the position of the virtual source is not known. By calculating dose ratios at a common distance from the target, this information is not needed.

3. EGS4 Monte Carlo Simulations

3.1 Introduction

All of the Monte Carlo calculations described in this report were carried out using the EGS4 code system with the PRESTAⁱⁱⁱ electron transport algorithm⁸. 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

ⁱⁱⁱ Parameter Reduced Electron - Step Transport Algorithm.

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^{iv}, documented by Nelson et al⁹, is used to generate data-sets of the required materials for subsequent use by EGS4.

3.2 Simulations of the NPL LINAC

The existing EGS4 user code NPLLINAC (NPLEGS Prototype Version 1.00) simulates the passage of electrons and photons through the NPL linear accelerator, see Figure 3.1, in order to calculate phase space spectra for all the standard photon qualities. 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 clinical beam additional filtration can be placed in the beam. The beam is described as lightly filtered when only the inherent filtration is present in the beam and heavily filtered when additional filtration is placed in the beam.

The NPLLINAC code stores 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 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. An existing FORTRAN program PARTFLU (version 1.02) was used to bin the phase space data calculated by NPLLINAC, see Figure 3.2 for an example binned phase space spectrum.

iv Pre-processor for EGS4.

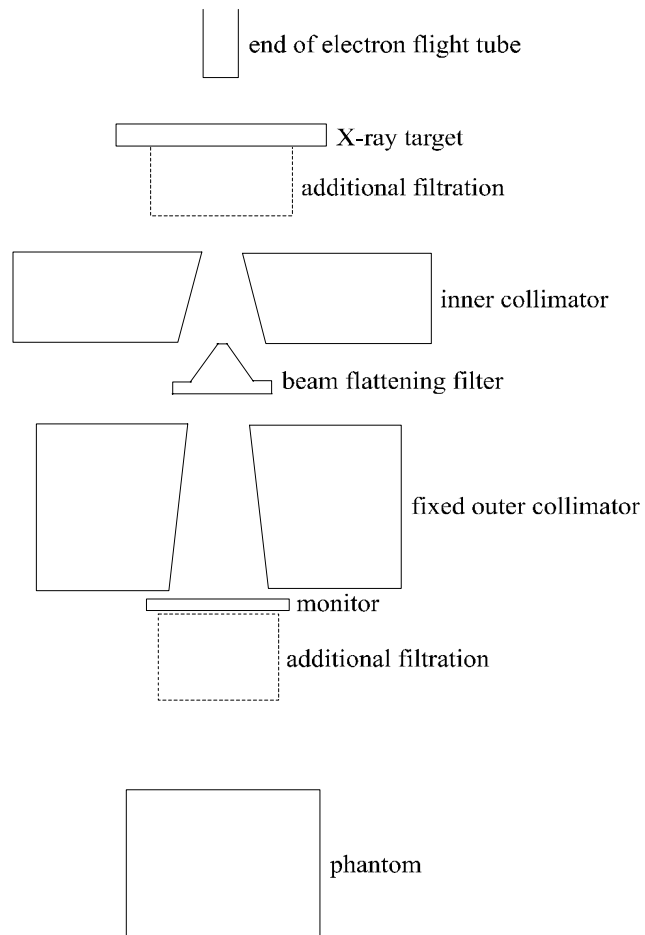


Figure 3.1: Schematic of NPL LINAC geometry

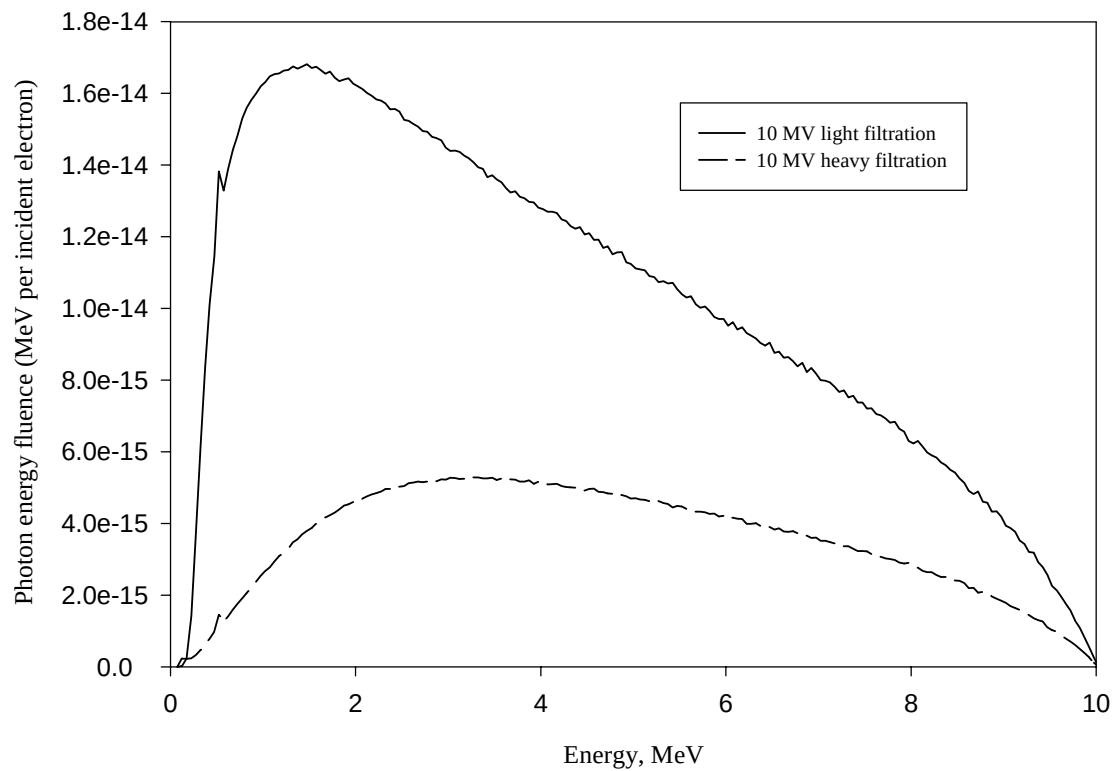


Figure 3.2: A Plot of calculated 10MV spectra with light and heavy filtration

3.3 Simulations of the measurement set up

Simulations of the measurement set up were carried out using the existing user-code DOSRZPAR that 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 or graphite phantom with a radius chosen to give the same area as the front face of the respective phantom used in the measurements. The phase space information generated using NPLLINAC was used by DOSRZPAR to calculate the total and primary dose to the scoring region at the points of measurement in the respective phantoms. The scoring region was approximated by a cylinder of length 1 cm, and radius 0.5 cm for target-chamber distances of 125 cm or less and radius 1 cm for greater target-chamber distances. In the case of the water phantom, the Perspex walls of the phantom were not modelled explicitly and so the entire phantom was modelled as water.

Simulations that were carried out to determine the correction for bremsstrahlung and annihilation radiation required modifications to DOSRZPAR to be made. These allowed the dose due to Compton and Rayleigh scattered photons to be scored separately to the contribution from bremsstrahlung photons and the contribution from annihilation photons. The code was validated by ensuring that conservation of dose was attained and that the total scatter contribution agreed with results from simulations carried out with an unmodified version of DOSRZPAR using the same initial random number seeds.

3.4 PEGS4 Data-sets

Within the PEGS4 input files used to create the data-sets for the NPLLINAC simulations the values of AE^v and AP^{vi} were set to 1.011 MeV and 0.1 MeV and the values of UE^{vii} and UP^{viii} were set to 20.511 MeV and 20.0 MeV for all materials. For the DOSRZPAR calculations the values of AE and AP were set to 0.7 MeV and 0.01 MeV and the values of UE and UP were set to 20.511 MeV and 20.0 MeV for all materials.

In both cases the IAPRIM¹⁰ and EPSTFL¹¹ 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 37¹². The EPSTFL option allows the user to input an arbitrary density-effect correction for use in calculating electron and positron collision stopping

^v The minimum (total) electron energy required for explicit δ -ray production

^{vi} Photon equivalent of AE

^{vii} The maximum (total) electron energy

^{viii} The maximum photon energy

powers. The density effect corrections were obtained using the program EPSTAR^{ix} (S.M. Seltzer - version 2.0B). These values were then used in conjunction with the PEGS4 input files to create the material data-sets.

4. Discussion of Uncertainties

4.1 Determination of Uncertainties

The following procedure for estimating uncertainties was used in order to comply with BIPM recommendations on the statement of uncertainty in which uncertainties estimated statistically are grouped as “type A” (random) and the rest are grouped as “type B” (non-random) and combined in quadrature to give an overall standard uncertainty (i.e. 1σ). Therefore the uncertainties in each component used in the calculation of N_w/N_c using Method A, see Table 4.1, and Method B, see Table 4.2, have been assessed.

4.2 Uncertainties in Method A

(All % standard uncertainties)	Type A (random)	Type B (non-random)
Q_w	0.06	0.05
Q_c	0.06	0.05
Q_c/Q_w	0.08	-
f_w	0.02	0.05
f_c	0.02	0.05
$(f_c/f_w)^2$	0.14	-
$F(1)$	-	0.15
$F(2)$	-	0.02
$F(3)$	-	0.05
$F(4)$	-	0.1
$(\mu_{en}/\rho)_w/(\mu_{en}/\rho)_c$	-	0.2
β_w/β_c	-	0.05
Total	0.16	0.28
Overall	0.32	

Table 4.1: Table of Uncertainties for Method A

^{ix} Calculates stopping power (collisional, radiative and total), CSDA ranges, bremsstrahlung yield for electrons (or positrons) with kinetic energies from 1 keV to 10 GeV and the mean excitation energy of the material.

Random and non-random uncertainties for ionisation measurements and target-chamber distances are given in Table 4.1. However, by taking ratios of these quantities the non-random uncertainties in both cases are reduced. The scaling value for the fluence ratio, $(f_c)^2/(f_w)^2$, has been corrected for the offset of the virtual source, F(1), air attenuation, F(2), and pair production, F(3). Therefore, the non-random uncertainty in each correction must be determined. The fluence ratio has not been corrected for bremsstrahlung and annihilation radiation, F(4), and so the non-random uncertainty in not applying this correction must also be determined.

Measurements made to determine the position of the virtual source were carried out for two different target positions for an energy of 10 MV as described in Section 2.2.5. The spread in the ratio of measured Q_c/Q_w corrected for the virtual source correction were compared for measurements made at the same target to chamber distances. It was assumed that the maximum spread observed in pairs of ratios was due to the combination of the uncertainties in the virtual source correction and the measurement uncertainties. This was observed to be 0.45% at the 3σ level, therefore, an estimate of 0.15% at the 1σ level was considered appropriate. The largest air attenuation correction which is applied to a pair of measurements is -0.86%. An estimate of the uncertainty in μ_{air} is 2 %, therefore, the uncertainty in the air attenuation correction is estimated to be 0.02%. The pair production correction and the bremsstrahlung and annihilation correction are both small corrections that at the highest energies are of the order 0.2% and 0.05% respectively. Of these corrections it was felt that the least well defined was the bremsstrahlung and annihilation correction and the corrections would contribute uncertainties of $\pm 0.05\%$ and $\pm 0.1\%$ respectively to the overall uncertainty.

The maximum ratio of mass-energy absorption coefficients in water to graphite for this work is of the order 1.13. The uncertainty in this value will be a combination of the uncertainty in the tabulated values and in the interpolation of these values and the uncertainty in the attenuated spectrum. A total uncertainty of 0.2% was considered appropriate for these contributions. The maximum correction for the centre of electron production is of the order 0.2% and it was considered that an estimated uncertainty of 0.05% was appropriate. Therefore the total uncertainty in the determination of N_w/N_c using Method A at the 1σ level was calculated to be 0.32%.

4.3 Uncertainties in Method B

(All % standard uncertainties)	Type A (random)	Type B (non-random)
Q_c/Q_w	0.09	-
D_w/D_c	0.3	0.2
Total	0.31	0.2
Overall	0.37	

Table 4.2: Table of Uncertainties for Method B

The values of N_w/N_c for Method B were determined by taking the product of the ratio of measured charge and the ratio of calculated absorbed dose. A random uncertainty in the measured value of Q_c/Q_w of 0.085% was considered appropriate. The value of D_w/D_c was determined using Monte Carlo techniques, which also determines the standard error of the mean on the dose values. Typically the values for the standard error of the mean were 0.3%. No reduction in the random uncertainty associated with approximations in the Monte Carlo method would be achieved by taking ratios of doses as might be expected when the set ups are similar. In this case the set ups are considerably different as the ratio of dose to water to dose to graphite at the same distance is required. Therefore the random uncertainty in the ratios of doses was 0.3%. The Monte Carlo calculations are strongly dependent on the ratio of the mass-energy absorption coefficients in water to graphite. Therefore, there is also a non-random uncertainty of 0.2% on the dose ratios. Therefore an overall uncertainty in the value of D_w/D_c of 0.36% is considered appropriate. Therefore the total uncertainty in the determination of N_w/N_c using Method B at the 1σ level was calculated to be 0.37%.

It is also worth noting that the non-random uncertainty in the ratios of mass-energy absorption coefficients is present in each total uncertainty for Methods A and B. This non-random uncertainty can, therefore, be ignored when comparing results from these two methods. Also, all random uncertainties can be reduced by a factor of $\sqrt{N}$, where N is the number of estimates made.

5. Results

5.1 Results for Method A

All results for 10 MV with light filtration are given in Tables 5.1 - 5.4 and in Figure 5.1. Tables 5.1 and 5.3 give values of the corrected ratio of photon energy fluences at the scaled measurement points in water and graphite phantoms with associated corrections. Tables 5.2 and 5.4 give values for all factors used in the determination of N_w/N_c as defined in Equation 2.20. Figure 5.1 presents a plot of N_w/N_c against target - chamber distance in water. Similarly the results for 10 MV heavy filtration are given in Tables 5.5 - 5.8 and in Figure 5.2. The overall values of N_w/N_c for all energies with both light and heavy filtration are given in Table 5.9 and in Figure 5.5. A comparison with values in present use at the NPL is given in Figure 5.6. For all Figures shown any points that are excluded from the determination of the mean are indicated in the key, see Section 6.

Distance to chamber in C, (cm)	Distance to chamber in W, (cm)	F(1)	F(2)	F(3)	Total Correction	Corrected $\frac{\psi_w}{\psi_c}$
*75.0	118.4	+1.36 %	-0.19 %	-0.08 %	+1.09 %	0.40562
*85.0	134.2	+1.20 %	-0.22 %	-0.08 %	+0.90 %	0.40478
95.0	150.0	+1.00 %	-0.24 %	-0.08 %	+0.68 %	0.40383
*95.0	150.0	+1.07 %	-0.24 %	-0.08 %	+0.75 %	0.40413
*118.4	187.0	+0.86 %	-0.30 %	-0.07 %	+0.49 %	0.40286
*125.0	197.4	+0.82 %	-0.32 %	-0.07 %	+0.43 %	0.40270
*134.2	211.9	+0.76 %	-0.35 %	-0.07 %	+0.34 %	0.40246
142.5	225.0	+0.67 %	-0.37 %	-0.07 %	+0.23 %	0.40202
*142.5	225.0	+0.72 %	-0.37 %	-0.07 %	+0.28 %	0.40222

* indicates a target position displaced by 2cm further from end of flight tube from normal position.

Table 5.1: Corrected ψ_w/ψ_c For 10 MV Light Filtration - Large Collimator

Distance to chamber in C, (cm)	Distance to chamber in W, (cm)	Corrected $\frac{\psi_w}{\psi_c}$	$\frac{Q_c}{Q_w}$	$\frac{(\mu_{en}/\rho)_w}{(\mu_{en}/\rho)_c}$	$\frac{\beta_w}{\beta_c}$	$\frac{N_w}{N_c}$
*75.0	118.4	0.40562	2.49934	1.1171	1.0010	1.1336
*85.0	134.2	0.40478	2.50589	1.1170	1.0010	1.1341
95.0	150.0	0.40383	2.51984	1.1170	1.0010	1.1378
*95.0	150.0	0.40413	2.51418	1.1170	1.0010	1.1361
*118.4	187.0	0.40286	2.52729	1.1169	1.0010	1.1383
*125.0	197.4	0.40270	2.52807	1.1169	1.0010	1.1382
*134.2	211.9	0.40246	2.52598	1.1169	1.0010	1.1366
142.5	225.0	0.40202	2.53021	1.1169	1.0010	1.1372
*142.5	225.0	0.40222	2.52799	1.1169	1.0010	1.1368

* indicates a target position displaced by 2cm further from end of flight tube from normal position.

Table 5.2: Method A Results For 10 MV Light Filtration - Large Collimator

Distance to chamber in C, (cm)	Distance to chamber in W, (cm)	F(1)	F(2)	F(3)	Total Correction	Corrected $\frac{\psi_w}{\psi_c}$
142.5	225.0	+0.72 %	-0.37 %	-0.07 %	+0.28 %	0.40222
213.75	337.5	+0.48 %	-0.55 %	-0.06 %	-0.13 %	0.40059

Table 5.3: Corrected ψ_w/ψ_c For 10 MV Light Filtration - Small Collimator

Distance to chamber in C, (cm)	Distance to chamber in W, (cm)	Corrected $\frac{\psi_w}{\psi_c}$	$\frac{Q_c}{Q_w}$	$\frac{(\mu_{en}/\rho)_w}{(\mu_{en}/\rho)_c}$	$\frac{\beta_w}{\beta_c}$	$\frac{N_w}{N_c}$
142.5	225.0	0.40222	2.53448	1.1169	1.0010	1.1397
213.75	337.5	0.40059	2.54098	1.1168	1.0010	1.1379

Table 5.4: Method A Results For 10 MV Light Filtration - Small Collimator

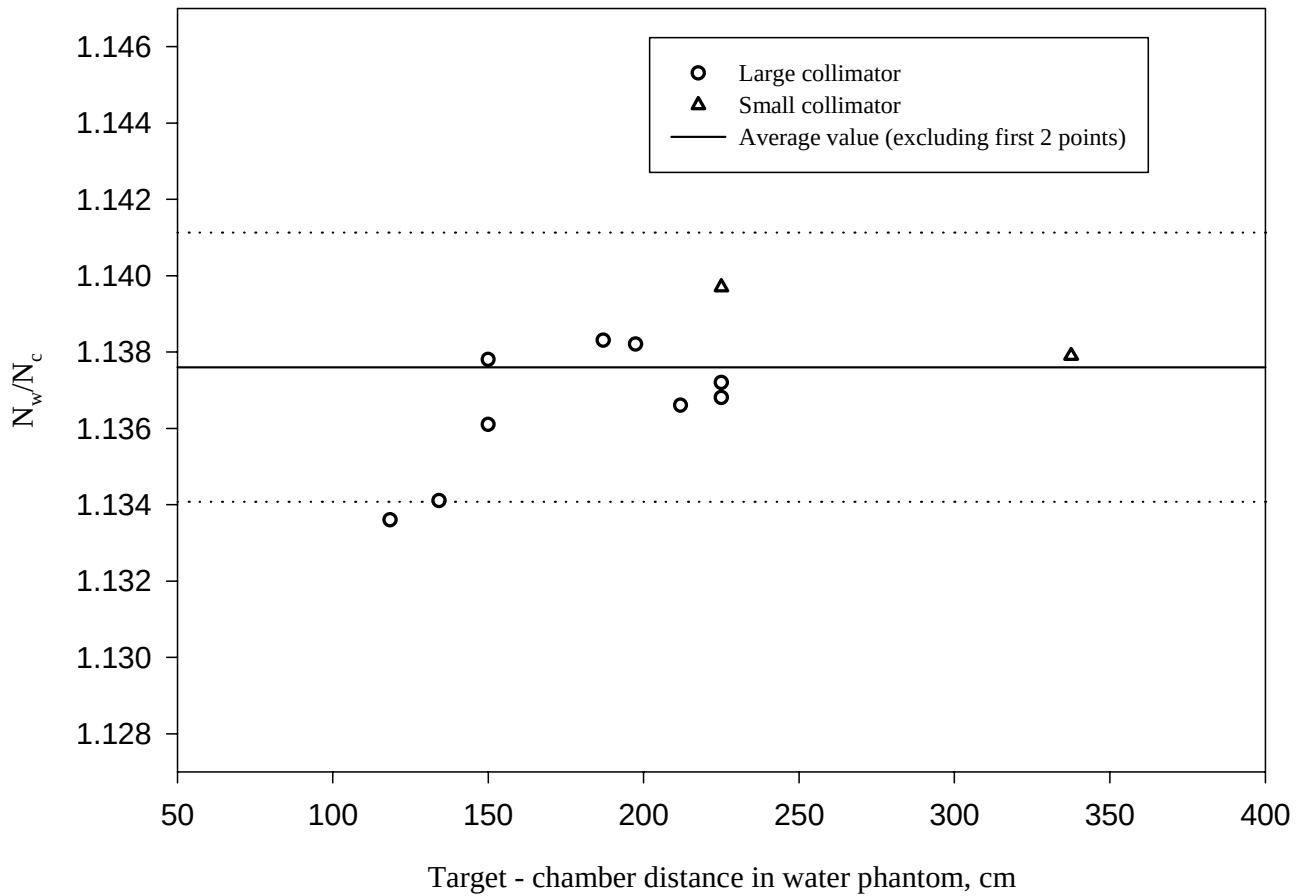


Figure 5.1: A Plot of N_w/N_c against target -chamber distance in water phantom for 10 MV - light filtration using Method A (dotted lines show 1σ uncertainty level on average value, see Section 4.2)

Distance to chamber in C, (cm)	Distance to chamber in W, (cm)	F(1)	F(2)	F(3)	Total Correction	Corrected $\frac{\psi_w}{\psi_c}$
75.0	118.4	+0.10 %	-0.16 %	-0.10 %	-0.16 %	0.40060
*75.0	118.4	+0.49 %	-0.16 %	-0.10 %	+0.23 %	0.40217
85.0	134.2	+0.09 %	-0.18 %	-0.10 %	-0.19 %	0.40040
*85.0	134.2	+0.43 %	-0.18 %	-0.10 %	+0.15 %	0.40178
95.0	150.0	+0.08 %	-0.20 %	-0.10 %	-0.22 %	0.40022
*95.0	150.0	+0.39 %	-0.20 %	-0.10 %	+0.09 %	0.40145
118.4	187.0	+0.06 %	-0.26 %	-0.10 %	-0.30 %	0.39969
*118.4	187.0	+0.31 %	-0.26 %	-0.10 %	-0.05 %	0.40068
*125.0	197.4	0.29 %	-0.27 %	-0.10 %	-0.08 %	0.40067
134.2	211.9	+0.05 %	-0.29 %	-0.10 %	-0.34 %	0.39975
*134.2	211.9	+0.27 %	-0.29 %	-0.10 %	-0.12 %	0.40062
142.5	225.0	+0.05 %	-0.31 %	-0.10 %	-0.36 %	0.39967
*142.5	225.0	+0.26 %	-0.31 %	-0.10 %	-0.15 %	0.40050

* indicates a target position displaced by 2cm further from end of flight tube from normal position.

Table 5.5: Corrected ψ_w/ψ_c For 10 MV Heavy Filtration - Large Collimator

Distance to chamber in C, (cm)	Distance to chamber in W, (cm)	Corrected $\frac{\Psi_w}{\Psi_c}$	$\frac{Q_c}{Q_w}$	$\frac{(\mu_{en}/\rho)_w}{(\mu_{en}/\rho)_c}$	$\frac{\beta_w}{\beta_c}$	$\frac{N_w}{N_c}$
75.0	118.4	0.40060	2.59862	1.1193	1.0012	1.1666
*75.0	118.4	0.40217	2.57706	1.1193	1.0012	1.1614
85.0	134.2	0.40040	2.55880	1.1193	1.0012	1.1481
*85.0	134.2	0.40178	2.55587	1.1193	1.0012	1.1508
95.0	150.0	0.40022	2.54874	1.1193	1.0012	1.1431
*95.0	150.0	0.40145	2.54742	1.1193	1.0012	1.1460
118.4	187.0	0.39969	2.55038	1.1193	1.0012	1.1423
*118.4	187.0	0.40068	2.54608	1.1193	1.0012	1.1432
*125.0	197.4	0.40067	2.54540	1.1192	1.0012	1.1428
134.2	211.9	0.39975	2.54761	1.1192	1.0012	1.1412
*134.2	211.9	0.40062	2.54589	1.1192	1.0012	1.1429
142.5	225.0	0.39967	2.54737	1.1192	1.0012	1.1408
*142.5	225.0	0.40050	2.54153	1.1192	1.0012	1.1406

* indicates a target position displaced by 2cm further from end of flight tube from normal position.

Table 5.6: Method A Results For 10 MV Heavy Filtration - Large Collimator

Distance to chamber in C, (cm)	Distance to chamber in W, (cm)	F(1)	F(2)	F(3)	Total Correction	Corrected $\frac{\Psi_w}{\Psi_c}$
125.0	197.4	+0.29 %	-0.27 %	-0.10 %	-0.08 %	0.40067
142.5	225.0	+0.26 %	-0.31 %	-0.10 %	-0.15 %	0.40050
150.0	236.84	+0.24 %	-0.32 %	-0.10 %	-0.18 %	0.40041
175.0	276.32	+0.21 %	-0.38 %	-0.10 %	-0.27 %	0.40001
197.4	311.63	0.19 %	-0.43 %	-0.10 %	-0.34 %	0.39987
213.75	337.5	0.17 %	-0.46 %	-0.10 %	-0.39 %	0.39955

Table 5.7: Corrected Ψ_w/Ψ_c For 10 MV Heavy Filtration - Small Collimator

Distance to chamber in C, (cm)	Distance to chamber in W, (cm)	Corrected $\frac{\Psi_w}{\Psi_c}$	$\frac{Q_c}{Q_w}$	$\frac{(\mu_{en}/\rho)_w}{(\mu_{en}/\rho)_c}$	$\frac{\beta_w}{\beta_c}$	$\frac{N_w}{N_c}$
125.0	197.4	0.40067	2.54118	1.1193	1.0012	1.1410
142.5	225.0	0.40050	2.53851	1.1193	1.0012	1.1393
150.0	236.84	0.40041	2.54078	1.1193	1.0012	1.1401
175.0	276.32	0.40001	2.54688	1.1192	1.0012	1.1416
197.4	311.63	0.39987	2.54852	1.1192	1.0012	1.1419
213.75	337.5	0.39955	2.54727	1.1192	1.0012	1.1405

Table 5.8: Method A Results For 10 MV Heavy Filtration - Small Collimator

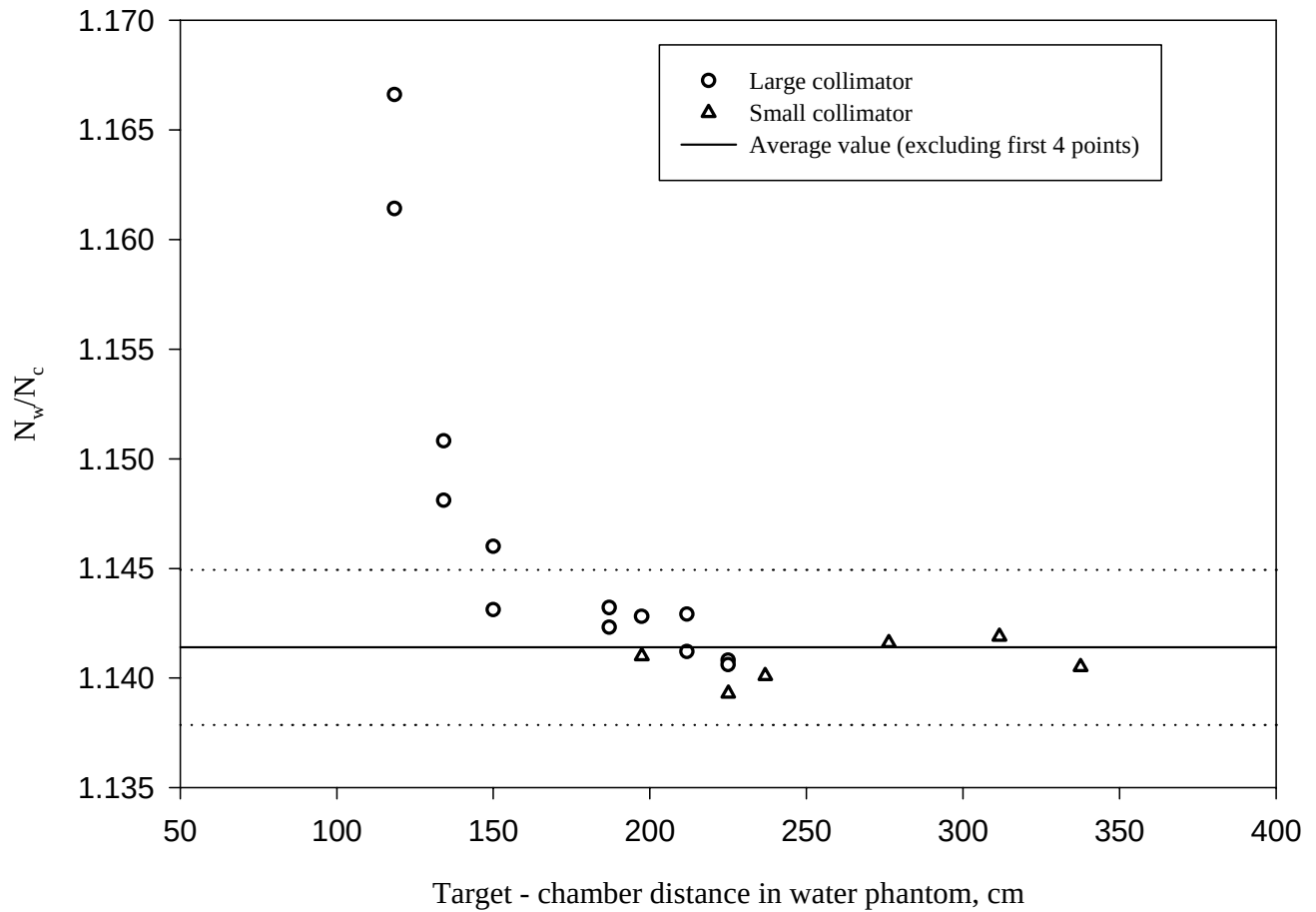


Figure 5.2: A Plot of N_w/N_c against target -chamber distance in water phantom for 10 MV - heavy filtration using Method A (dotted lines show 1σ uncertainty level on average value, see Section 4.2)

Energy (Filtration)	TPR	Corrected $\frac{\Psi_w}{\Psi_c} \cdot \frac{Q_c}{Q_w}$	Average $\frac{(\mu_{en}/\rho)_w}{(\mu_{en}/\rho)_c}$	Average $\frac{\beta_w}{\beta_c}$	$\frac{N_w}{N_c}$	1σ standard error on the mean (%)
4 MV (L)	0.584	1.0117	1.1117	1.0004	1.1251	0.04
4 MV (H)	0.621	1.0144	1.1117	1.0004	1.1284	0.04
6 MV (L)	0.646	1.0155	1.1131	1.0006	1.1311	0.04
6 MV (H)	0.670	1.0184	1.1135	1.0006	1.1346	0.04
8 MV (L)	0.679	1.0151	1.1149	1.0008	1.1327	0.10
8 MV (H)	0.717	1.0171	1.1162	1.0009	1.1363	0.09
10 MV (L)	0.704	1.0175	1.1169	1.0010	1.1376	0.04
10 MV (H)	0.746	1.0186	1.1192	1.0012	1.1414	0.03
12 MV (L)	0.723	1.0174	1.1192	1.0012	1.1401	0.04
12 MV (H)	0.758	1.0189	1.1214	1.0014	1.1442	0.06
16 MV (L)	0.750	1.0169	1.1228	1.0016	1.1436	0.06
16 MV (H)	0.779	1.0177	1.1253	1.0018	1.1472	0.07
19 MV (L)	0.763	1.0164	1.1252	1.0018	1.1457	0.05
19 MV (H)	0.790	1.0155	1.1278	1.0020	1.1476	0.12

Table 5.9: Method A Results For All Energies

5.2 Results for Method B

Ratios of measured collected charge and absorbed dose calibration factors in water and graphite are given in Tables 5.10 and 5.11 for 10 MV with light filtration. Similarly the values for 10 MV with heavy filtration are given in Tables 5.12 and 5.13. Figures 5.3 and 5.4 give plots of N_w/N_c against target -chamber distance for 10 MV with light and heavy filtration. The values of D_w/D_c , determined using Monte Carlo methods, are 1.0948 for 10 MV with light filtration and 1.1057 for 10 MV with heavy filtration. The overall results for all energies with light and heavy filtration are given in Table 5.14 and in Figure 5.5. A comparison with values currently in use at the NPL is given in Figure 5.6.

Target to Chamber Distance (cm)	$\frac{Q_c}{Q_w}$	$\frac{N_w}{N_c}$
*75.0	1.03938	1.1379
85.0	1.04057	1.1392
*85.0	1.03842	1.1369
95.0	1.03881	1.1373
*95.0	1.03813	1.1365
*118.4	1.03771	1.1361
125.0	1.03934	1.1379
*125.0	1.03825	1.1367
*134.2	1.03739	1.1357
142.5	1.03813	1.1365
*142.5	1.03824	1.1367
150.0	1.03850	1.1369
*150.0	1.03767	1.1360

*indicates a target position displaced by 2cm further from end of flight tube from normal position.

Table 5.10: Method B Results For 10 MV Light Filtration - Large Collimator

Target to Chamber Distance (cm)	$\frac{Q_c}{Q_w}$	$\frac{N_w}{N_c}$
125.0	1.03816	1.1366
142.5	1.03955	1.1381
150.0	1.03733	1.1357
213.75	1.03738	1.1357
225.0	1.03777	1.1361

Table 5.11: Method B Results For 10 MV Light Filtration - Small Collimator

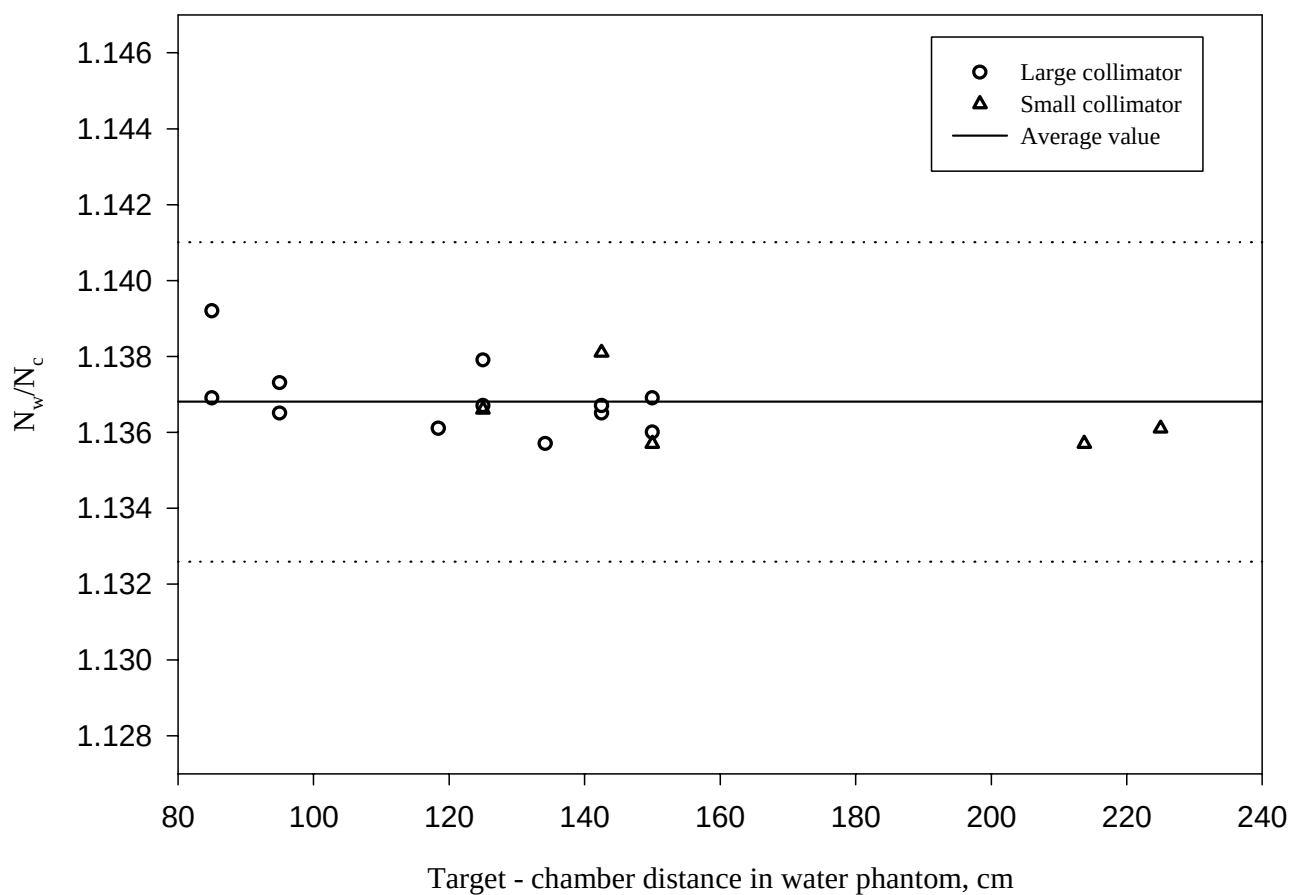


Figure 5.3: A Plot of N_w/N_c against target -chamber distance for 10 MV - light filtration using Method B (dotted lines show 1σ uncertainty level on average value, see Section 4.3)

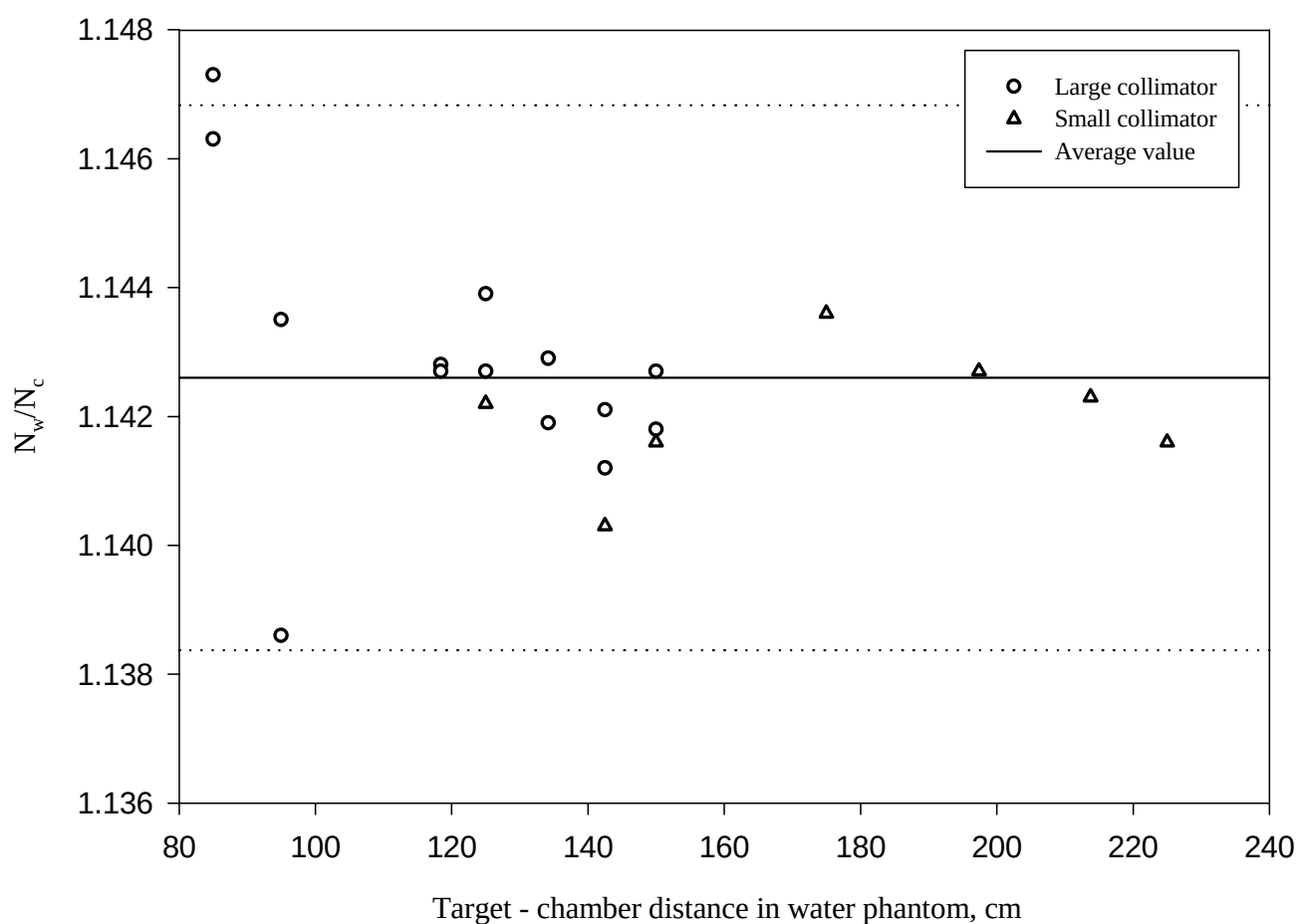
Target to Chamber Distance (cm)	$\frac{Q_c}{Q_w}$	$\frac{Q_c}{Q_w} \cdot \frac{D_w}{D_c}$
75.0	1.03378	1.1431
*75.0	1.03366	1.1429
85.0	1.03762	1.1473
*85.0	1.03675	1.1463
95.0	1.02977	1.1386
*95.0	1.03419	1.1435
118.4	1.03357	1.1428
*118.4	1.03346	1.1427
125.0	1.03348	1.1427
*125.0	1.03451	1.1439
134.2	1.03276	1.1419
*134.2	1.03367	1.1429
142.5	1.03295	1.1421
*142.5	1.03208	1.1412
150.0	1.03266	1.1418
*150.0	1.03344	1.1427

* indicates a target position displaced by 2cm further from end of flight tube from normal position.

Table 5.12: Method B Results For 10 MV Heavy Filtration - Large Collimator

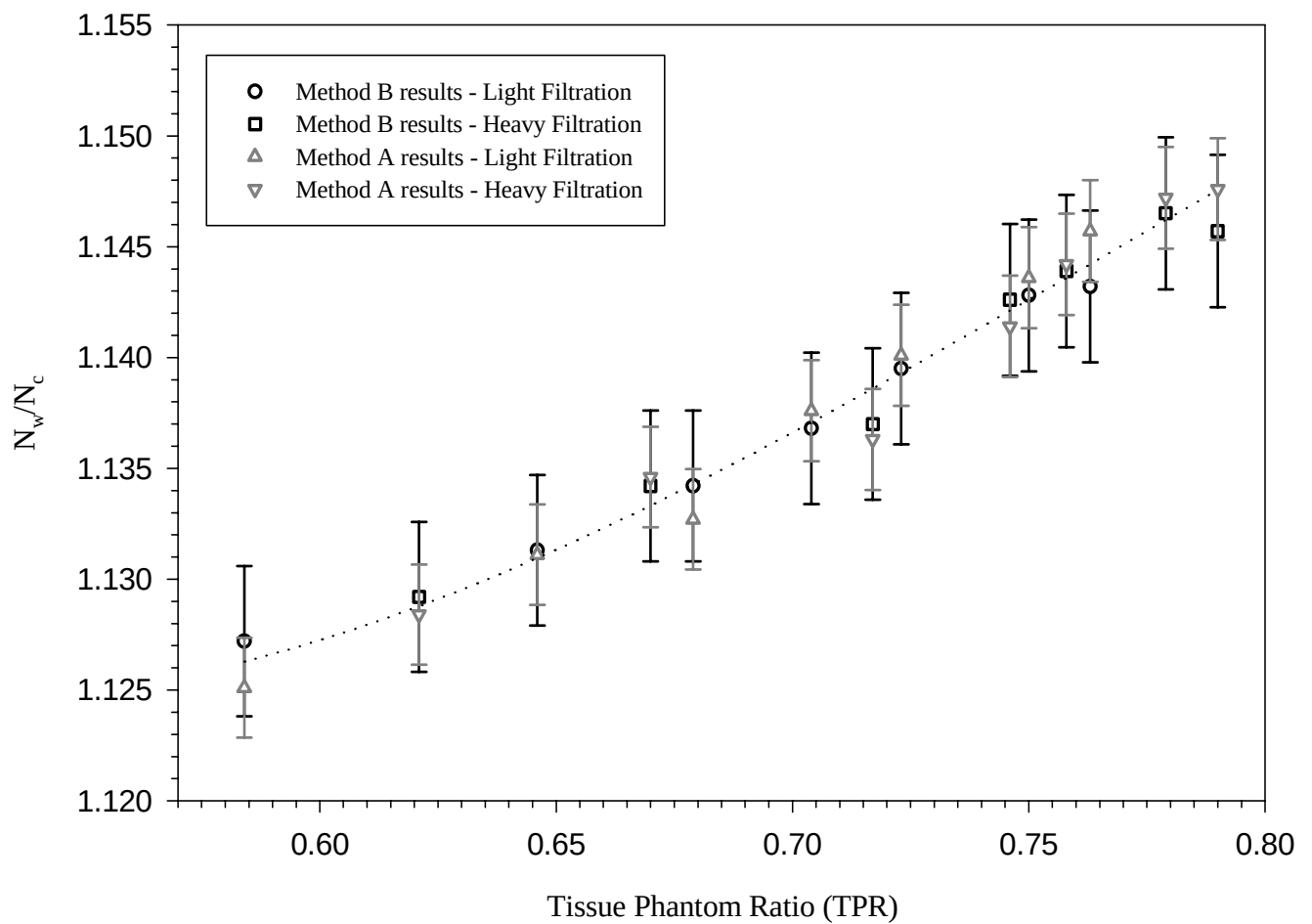
Target to Chamber Distance (cm)	$\frac{Q_c}{Q_w}$	$\frac{Q_c}{Q_w} \cdot \frac{D_w}{D_c}$
125.0	1.03297	1.1422
142.5	1.03129	1.1403
150.0	1.03244	1.1416
175.0	1.03423	1.1436
197.4	1.03343	1.1427
213.75	1.03306	1.1423
225.0	1.03249	1.1416

Table 5.13: Method B Results For 10 MV Heavy Filtration - Small Collimator

Figure 5.4: A Plot of N_w/N_c against target -chamber distance for 10 MV - heavy filtration using Method B (dotted lines show 1σ uncertainty level on average value, see Section 4.3)

	TPR	$\frac{Q_c}{Q_w}$	$\frac{D_w}{D_c}$	$\frac{N_w}{N_c}$
4 MV (L)	0.584	1.0509	1.0726	1.1272
4 MV (H)	0.621	1.0446	1.0810	1.1292
6 MV (L)	0.646	1.0438	1.0838	1.1313
6 MV (H)	0.670	1.0423	1.0882	1.1342
8 MV (L)	0.679	1.0394	1.0912	1.1342
8 MV (H)	0.717	1.0353	1.0982	1.1370
10 MV (L)	0.704	1.0384	1.0948	1.1368
10 MV (H)	0.746	1.0334	1.1057	1.1426
12 MV (L)	0.723	1.0424	1.0931	1.1395
12 MV (H)	0.758	1.0364	1.1038	1.1439
16 MV (L)	0.750	1.0368	1.1023	1.1428
16 MV (H)	0.779	1.0322	1.1108	1.1465
19 MV (L)	0.763	1.0337	1.1059	1.1432
19 MV (H)	0.790	1.0287	1.1137	1.1457

Table 5.14: Method B Results For All Energies

Figure 5.5: A Plot of N_w/N_c against TPR for all mega-voltage X-ray energies for Methods A and B (uncertainties shown are at 1 σ level, see Sections 4.2 and 4.3)

	TPR	$\frac{N_w}{N_c}$ (1)	$\frac{N_w}{N_c}$ (2)	Spread (%)
4 MV (L)	0.584	1.1263	1.1306	-0.4
4 MV (H)	0.621	1.1288	1.1325	-0.3
6 MV (L)	0.646	1.1309	1.1339	-0.3
6 MV (H)	0.670	1.1333	1.1354	-0.2
8 MV (L)	0.679	1.1343	1.1362	-0.2
8 MV (H)	0.717	1.1386	1.1385	+0.0
10 MV (L)	0.704	1.1371	1.1379	-0.1
10 MV (H)	0.746	1.1421	1.1409	+0.1
12 MV (L)	0.723	1.1393	1.1394	-0.0
12 MV (H)	0.758	1.1436	1.1417	+0.2
16 MV (L)	0.750	1.1426	1.1409	+0.1
16 MV (H)	0.779	1.1462	1.1435	+0.2
19 MV (L)	0.763	1.1442	1.1424	+0.2
19 MV (H)	0.790	1.1476	1.1445	+0.3

(1) values determined for this work.

(2) values currently in use at the NPL.

Table 5.15: Values determined for all energies from best fit to results

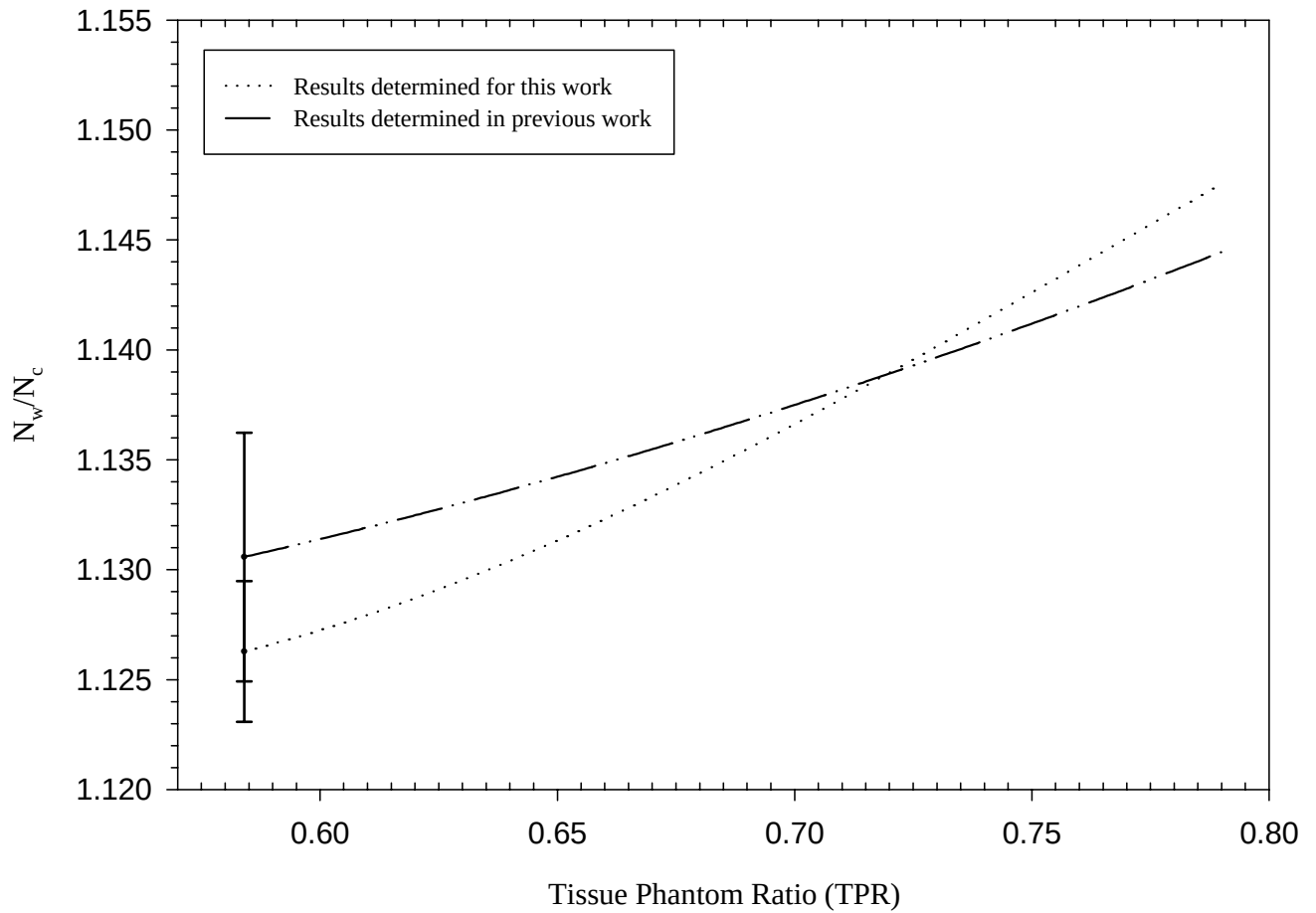


Figure 5.6: A Plot of N_w/N_c against TPR for all mega-voltage X-ray energies for this work and for values currently in use at the NPL (error bars shown are the total uncertainty quoted on the photon fluence scaling theorem results)

6. Discussion of Results

The values of N_w/N_c determined using Methods A and B agree to within 1σ uncertainty where the uncertainties on Method A results are 0.20% and the uncertainties on Method B results are 0.30%. Non-random uncertainties common to both methods have not been included in each total uncertainty and all random uncertainties are reduced by a factor of $\sqrt{N}$, where N is the number of estimates made. The best fit to both sets of results agrees with values determined in previous work to within 2σ uncertainty, the greatest discrepancy being found at the lowest and highest energies.

When determining the virtual source correction it was noted that for lightly filtered qualities at all energies there was a noticeable decrease in the measured chamber to monitor charge ratio close to the collimator. This was explained by an increase in the charge collected in the monitor chamber due to backscatter from the water phantom. For measurements made using method A the phantoms were set up at scaled distances from the target where the graphite phantom was set up closer to the target than the water phantom. It was observed that, as expected, the value of Q_c/Q_w was low at short distances on comparison to measurements made further away from the target. This effect was also observed in former work that determined the values in current use at the NPL. Previously, no explanation could be concluded, however, it was determined that the values at short distance were too low and so were increased by 0.5%. For this work measurements made at a focal distance of less than 95 cm were not used in determining the average value of N_w/N_c .

It was also found that, when determining the virtual source correction, for heavily filtered qualities there was a noticeable increase in the measured chamber to monitor charge ratio close in to the collimator. This can be explained by radiation, scattered in the collimator and/or the additional filtration, reaching the chamber at measurement distances close to the collimator. It was observed that, as expected, the value of Q_c/Q_w was high at short distances on comparison to measurements made further away from the target. For this work measurements made at a focal distance of less than 125 cm for energies up to 8 MV and less than 118.4 cm for energies above 8 MV were not used in determining the average value of N_w/N_c .

7. Conclusions

One of the main aims of this work was to determine whether the interpolation and extrapolation of results from values for light filtration to give values for heavy filtration was an adequate method. It can be seen from Figure 5.5 that, for this work, no noticeable difference was observed between results for light and heavy filtration measurements. It can therefore be concluded that this method was adequate.

The values of N_w/N_c determined in this work agree to within 1σ uncertainty to values in present use at the NPL. The uncertainty quoted on the values in present use is $\pm 0.5\%$, however, it is worth noting that much of the work used to determine the values of N_w/N_c in both cases makes use of the photon fluence scaling theorem. Therefore, non-random uncertainties common to both results should not strictly be included when comparing values of N_w/N_c . The greatest discrepancy between the two sets of results is observed to be at the extremes of the energy range with the largest difference (0.4%) at 4 MV with light filtration. Further work is required to determine the value of N_w/N_c for a ^{60}Co beam. New facilities are soon to be commissioned at the NPL that will allow measurements in ^{60}Co to be made at a greater range of distances.

8. References

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