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**Re-establishing the absorbed dose primary standard for
photon beams on the NPL clinical linac**

J A D PEARCE, D R SHIPLEY and S DUANE

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J A D Pearce, D R Shipley and S Duane
Acoustics & Ionising Radiation Division

ABSTRACT

The NPL Elekta clinical linac was officially opened in November 2008. Since then, graphite calorimetry with the existing primary standard calorimeter and ionisation chamber measurements in both graphite and water phantoms have been made at each of the seven available x-ray energies. Monte Carlo simulations of the NPL Elekta linac, the existing primary standard calorimeter and both graphite and water phantoms have also been completed in support of the measurements to enable the complete realisation of absorbed dose to water for photon beams. This report describes the work that was carried out to re-establish the existing UK primary standard of absorbed dose to water on this new facility for use in the photon therapy level calibration services offered by NPL. A set of reference 2611 type ionisation chambers were calibrated in terms of absorbed dose to water, N_w , with a total standard uncertainty of 0.49% ($k=1$). The values of k_Q , the ratio of the calibration factor at a beam quality Q to that in a cobalt-60 beam, show good agreement (within 0.4%) with k_Q values currently in use with a standard uncertainty 0.56% ($k=1$). For now, 2611 ionisation chamber calibrations will continue to be reported by normalising the existing k_Q curve, however this will be reconsidered when the new NPL primary standard calorimeter is commissioned and sufficient data from this new calorimeter is available.

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National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

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Approved on behalf of NPLML by Bajram Zeqiri, Knowledge Leader,
Acoustics and Ionising Radiation Division.

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1 INTRODUCTION

A new state-of-the-art clinical linac facility was opened in November 2008 at the National Physical Laboratory (NPL) in addition to the existing research linac facility, whose linac is now over 40 years old. The new machine is an Elekta Synergy Digital Linac with iViewGT portal and XVI 3D x-ray volumetric imaging, MOSAIQ management system and Pinnacle treatment planning system. In particular, its specification conforms to the recent recommendations of the National Radiotherapy Advisory Group that all new and replacement machines in UK hospitals be capable of image-guided 4D adaptive radiotherapy, which can target tumours more accurately. The NPL machine can be configured to deliver seven x-ray beam energies (instead of the usual maximum of three in any one hospital machine). This feature, together with the ability to provide up to ten electron beam energies, will enable NPL to provide absorbed dose calibrations for the full range of energies currently in therapeutic use in the UK.

The NPL is responsible for maintaining the UK primary standards of absorbed dose to water in both high-energy photon and electron beams. For photons, the primary standard is a graphite calorimeter (DuSautoy, 1991) that directly measures absorbed dose to graphite, that is, the energy deposited in a small graphite core at the centre of the calorimeter, in ^{60}Co gamma ray and MV x-ray beams, divided by the mass of the core. The current status of calorimetric primary standards of absorbed dose has been reviewed (Seuntjens and Duane, 2008).

Dissemination of the absorbed dose primary standard is done via calibration of a set of reference standard ionisation chambers. These chambers are placed in a graphite phantom and their response compared with that of the primary standard in terms of absorbed dose to graphite. These calibrations are then converted to absorbed dose to water using two possible methods: one involving charge measurements at a constant target-chamber distance, and the second through the application of the photon fluence scaling theorem (Nutbrown *et al.* 2000, Pruitt and Loevinger, 1982). Secondary standard instruments are then calibrated against these reference standards at either 5cm or 7cm depth in a water phantom. Chamber calibrations are normally given in terms of k_Q , the ratio of the chamber calibration factor in a given quality, Q, to that in a reference quality, Q_0 (^{60}Co γ -rays at NPL) where the radiation quality is defined in terms of tissue-phantom ratio ($\text{TPR}_{20/10}$).

The present work includes calorimetry with the primary standard graphite calorimeter and chamber measurements in both graphite and water phantoms in all seven x-ray beams on the NPL clinical linac. Monte Carlo methods have also been used to determine a number of corrections in support of these measurements, in particular, corrections to account for the presence of non-graphite materials and air/vacuum gaps in the primary standard calorimeter, water-to-graphite dose ratios in the phantoms, and corrections for the different geometrical configuration of the calorimeter and graphite chamber phantom. Values for the factors to convert absorbed dose calibrations from graphite to water have then been re-evaluated for each new clinical x-ray energy and compared with previously determined data for the x-ray beams on the existing research linac.

2 METHODS AND MATERIALS

2.1 NPL CLINICAL LINAC

The NPL clinical linac is an Elekta Synergy® machine and has seven available x-ray energies. These are in the form of three "handbags" with each handbag offering three different x-ray energies. The combinations are as follows:

Handbag 1: 6, 10, 15 MV x-rays, Handbag 2: 6, 10, 25 MV x-rays, Handbag 3: 4, 8, 18 MV x-rays.

For all chamber and calorimeter measurements in this work, a non-wedged $10 \times 10 \text{ cm}^2$ field defined using the multi-leaf collimator (MLCi) leaves and backup diaphragms was used at a source-to-

chamber distance (SCD) of 100 cm. Measurements were made at each x-ray energy using a horizontal beam, with the gantry angle set to 90° and the collimator angle set to 0°. It should also be noted here that the two duplicate energies, namely 6 and 10 MV x-rays, in handbags 1 and 2 are identical.

2.2 CALIBRATION PROCEDURE AND DETERMINATION OF k_Q .

The current UK primary standard for absorbed dose measurement in photon beams is a graphite calorimeter that was developed at NPL during the 1980s. The calorimeter is cylindrical in shape and based on the design of Domen (Domen and Lamperti, 1974) and described in detail by DuSautoy (1991).

The primary standard calorimeter realises absorbed dose to graphite, $D_{g,cal}$, in ^{60}Co γ -rays and in MV x-rays from an absolute measurement of the dose deposited in the graphite core, D_{core} . A correction k_{gap} is required to account for the presence of gaps and other non-graphite materials in the calorimeter to give the dose at the position of the core in homogenous graphite.

$$D_{g,cal} = D_{core} \cdot k_{gap} \quad (1)$$

Reference standard ionisation chambers are then calibrated against the calorimeter in a graphite phantom in terms of absorbed dose to graphite, $D_{g,ch}$. The graphite phantom is square in cross-section (having a smaller cross sectional area than the calorimeter) and also deeper with more material behind the chamber than the calorimeter. Ideally, the reference chambers should be positioned at the same depth (i.e. mass thickness) in the graphite phantom as the depth of the core in the calorimeter. However, this is not always possible and so a small depth correction, k_{depth} , is required to correct the calorimeter dose to that at the chamber measurement depth in the graphite phantom. Secondly, a correction k_{geom} is also needed to account for the different geometrical configurations of the calorimeter and phantom that results in differing amounts of scatter at the core and chamber positions respectively. Other small corrections, k_i , may also be required for beam uniformity and small setup differences in the source-chamber/core distance. So:

$$D_{g,ch} = D_{g,cal} \cdot k_{depth} \cdot k_{geom} \cdot \Pi_i k_i \quad (2)$$

The absorbed dose to graphite calibration factor for the chamber, N_g , is then obtained from the ratio of the dose at the position of the chamber in the graphite phantom, $D_{g,ch}$, and the charge measured by the chamber, $Q_{g,ch}$, after correction to standard conditions of temperature (273.15K) and pressure (101.325kPa) and to zero ion recombination (determined experimentally):

$$N_g = \frac{D_{g,ch}}{Q_{g,ch}} \quad (3)$$

The absorbed dose to graphite calibration is then converted to absorbed to water, N_w , via a suitable dose conversion method:

$$N_w = N_g \cdot \frac{D_w}{D_g} \cdot \frac{Q_g}{Q_w} \quad (4)$$

where D_w is the dose at the position of the chamber at the equivalent depth (at either 5 or 7cm, depending on beam energy) in a water phantom and Q_w is the charge measured by the chamber at that point, and D_g and Q_g are the dose and charge measured at the chamber position in the graphite phantom, from equation (3).

There are two possible methods to convert the absorbed dose to graphite to absorbed dose to water and both are described in detail by Nutbrown *et al* (2000), Nutbrown *et al* (2002) and Burns and Dale (1990). In summary, these are:

- Scaling dose ratio method: this uses the photon fluence scaling theorem and involves *scaling* all phantom dimensions and depths by the inverse ratio of electron densities of the two media to ensure that the proportions of scattered to primary radiation at the scaled points of measurement are the same. Here the ratio, D_w/D_g , simplifies to:

$$\frac{D_w}{D_g} = \left(\frac{f_g}{f_w} \right)^2 \cdot \left(\frac{\mu_{en}}{\rho} \right)_{w,g} \cdot \beta_{w,g} \cdot \Pi_i \cdot k_i \quad (5)$$

where, f_w , and, f_g , are the distances from the source to the chamber, $(\mu_{en}/\rho)_{w,g}$, is the ratio of mass attenuation coefficients, and, $\beta_{w,g}$, is the ratio of absorbed dose to collision kerma, at the measurement point in the water and graphite phantoms respectively. A number of other corrections, k_i , are also required as the assumptions of the photon fluence scaling theorem are not all met in reality. These include a virtual source correction to account for deviations from the inverse square law, and a correction to account for non-Compton interactions. Both Monte Carlo methods and experimental measurements are required in this method.

- Equidistant dose ratio method: this involves making charge measurements at a *constant* source-chamber distance and at scaled depths in the two phantoms. Monte Carlo methods are then used to directly calculate the ratio of dose to water to dose to graphite, D_w/D_g , at the respective points in the two phantoms.

As before, an additional small depth correction, $k_{depth-conv}$, may also be needed in each method to correct the dose at the measurement position of the chamber in the water phantom to the required scaled depth. The previous work carried out for all mega-voltage x-ray beams on the existing research linac showed close agreement between both methods and so in this work only the equidistant ratio method has been used.

The calibration factors for the reference ionisation chambers, N_w , are normally given in terms of k_Q :

$$k_Q = \frac{N_{w,Q}}{N_{w,Q_0}} \quad [Q_0: {}^{60}\text{Co}] \quad (6)$$

that is, the ratio of the calibration factor $N_{w,Q}$, at a given energy or radiation quality Q , to that determined in a reference quality, Q_0 , (${}^{60}\text{Co}$ γ -rays at NPL).

2.3 NPL PHOTON CALORIMETRY

In photon beam calorimetry at NPL an external monitor chamber of type PTW-786 is used as the transfer instrument between the calorimeter and reference standard ionisation chambers. The PTW monitor was mounted on the linac head in the accessory tray and connected to an electrometer. A 3mm sheet of Tufnol™ was positioned immediately upstream of the monitor chamber to provide build up and more stable charge readings. A calibrated thermistor was placed between this build up and the PTW monitor chamber to enable determination of the temperature inside the PTW monitor. The NPL graphite calorimeter was set up alongside the graphite chamber phantom on the linac carriage. Both were configured for a measurement depth in graphite equivalent to either 5g.cm⁻² of water for energies up to and including 10 MV, or 7g.cm⁻² for energies above 10 MV.

For the graphite calorimeter, graphite plates labelled 20 (thickness 19.99 mm), 4 and 2 were added in front of the core plate for low-energy measurements, and plates labelled 20, 8 and 10 were added for high-energy measurements. The centre of the calorimeter core is located 7.83 mm behind the front face.

A schematic diagram of the calorimeter is shown in Figure 1.

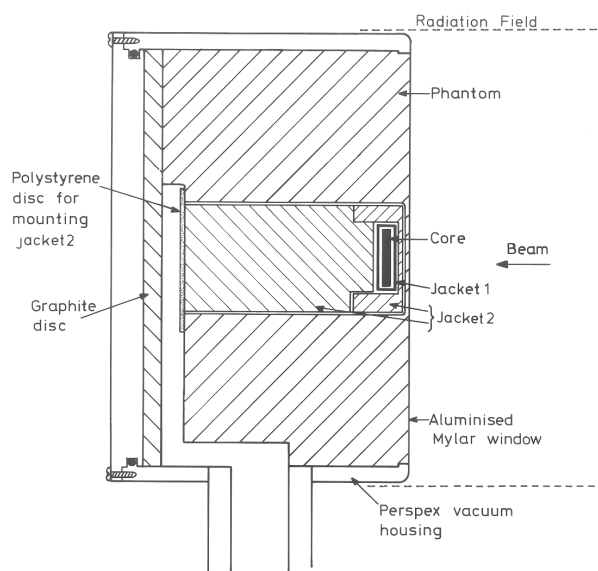


Figure 1. A schematic diagram of the NPL primary standard graphite calorimeter.

To position the calorimeter on axis, build up plate 20 that is positioned in front of the core-containing plate was removed. A white paper disc with black lines crossing in the centre was used to mark the centre of the calorimeter core and the linac light field indicator was used to position the calorimeter on axis. A mirror tile was positioned on the front of the calorimeter and used to reflect the light field indicator lines back to the linac to ensure the calorimeter was perpendicular to the beam. The calorimeter was positioned such that the core was at a distance from the source of 100 cm, using an internal micrometer between plate 20 and the front pointer holder attached as a linac accessory.

Traceability of the calorimeter energy depends on measurement of voltage across and current through the core heating thermistor. Two Solartron 7061 dvms were calibrated using a voltage standard.

The NPL graphite calorimeter is operated in isothermal mode. In this mode, electrical heaters in jacket 1 and jacket 2 are used to ensure that the temperature of the calorimeter is kept constant; as the core temperature increases due to energy deposited by ionising radiation, the power injected by the heaters is decreased, such that the core temperature remains constant. The electrical power is limited, with the result that effective substitution of radiation heating is possible up to a maximum dose rate of approximately 3 Gy/min in photon beams.

The operation of the primary standard is a complex process; the calorimeter is controlled using a control program written and run in HTBasic. Data were acquired by running the calorimeter control program in thermostatic (active isothermal) mode while the linac delivered x-rays for approximately 1 minute, determined by setting the number of monitor units (MUs) equal to the dose rate in MU/minute. Generally, half of the maximum available dose rate was used to enable the calorimeter heaters to compensate for changes in core temperature during irradiation. The exception to this was at 4 MV where calorimeter control remains possible at the maximum available dose rate (2.5 Gy/min). Step changes in the heater powers (squared heater voltages) were scheduled to occur around beam on/off and improve the isothermal performance. The corresponding charge recorded by the external

PTW monitor chamber was also recorded, along with temperature and pressure readings for each measurement, enabling calibration of the monitor in terms of grays per monitor volt.

Several calorimeter measurements were made over the course of a day. 120s pre-irradiation drift was allowed before each run. Analysis of calorimeter measurements involves determining

- the time-dependent core electrical heating power, by correcting measurements of the core heating thermistor current and voltage for the small leakage from first and second jacket heater supplies,
- the time-dependent correction for heat transfer to the core, based on measured changes in the temperatures of the core and first jacket, and the power of the first jacket heater,
- the energy absorbed by the calorimeter core as the time integral of the radiation heating power,
- the best four parameter fit to the core energy as a function of time before and after the radiation heating (three parameters allow for a quadratic approximation to an underlying drift, and one parameter represents the total energy absorbed from radiation),
- the mean and standard deviation of the absorbed dose to graphite at the calorimeter measurement point as the energy absorbed from radiation divided by the effective core mass; a number of corrections are also applied to enable determination of the absorbed dose to graphite, see below for details.

2.4 GRAPHITE PHANTOM MEASUREMENTS

NPL maintains a set of several reference ionisation chambers that are calibrated in a graphite phantom by comparison with the NPL graphite calorimeter. These reference ionisation chambers are of type 2611. Table 1 lists the graphite plates used for the graphite chamber phantom, for both low energy (4-10 MV) and high energy (15-25 MV) x-ray beams.

Table 1. Measured density of blocks of graphite phantom (Nutbrown *et al* 2000)

Plate number	Purpose	Density g cm^{-3}	Thickness	
			mm	g cm^{-2}
4	High energy only build-up	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

The graphite chamber phantom was set up with plate 13 as build up. There is a pencil cross on the front of this plate that was used to align the chamber phantom on the beam axis using the light field. The chamber measurement point was positioned at a distance of 100 cm from the source in the same way as the calorimeter. A calibrated thermistor was taped to the phantom surface to measure chamber temperature. Pressure was monitored using a calibrated Druck DPI142 barometer. The PTW monitor chamber was also used for these measurements in order to transfer the calibration from the calorimeter.

Each reference chamber was connected in turn to an electrometer and 50 MU at the same dose rate as that used for the calorimetry were delivered to the chamber. The charge collected by the chamber was recorded and the associated temperature and pressure readings. Concurrently, the charge collected by the external PTW monitor chamber as well as its temperature and pressure was recorded.

Measurements with the reference standard chambers were made at the start and the end of each day, before and after the calorimetry measurements, to minimise the effects of any drift in linac output. All measurements were corrected to standard temperature and pressure conditions of 275.15K and

101.325 kPa. A correction for ion recombination was applied to all reference standard measurements. The monitor ionisation was not corrected for recombination.

To enable determination of the depth correction k_{depth} , to account for the difference in mass thickness between the calorimeter core and the chamber measurement point in the graphite phantom, a small set of measurements were made at different depths in the phantom. The usual build up plate positioned at the front of the phantom (either plate 4 or 13, as listed in Table 1) was replaced by several plates with the same total thickness. Measurements were made at the reference depth in graphite, and ± 2 mm and ± 4 mm. This enabled determination of a small portion of ionisation as a function of depth in graphite. A fit was then applied to the resulting depth-ionisation curve to determine the correction k_{depth} .

2.5 DOSE CONVERSION MEASUREMENTS

In order to provide a calibration service in terms of absorbed dose to water it is necessary to evaluate factors to convert from absorbed dose to graphite to absorbed dose to water for all energies. Previous work (Nutbrown *et al* 2000) gave a highly detailed explanation of how these factors are determined and the methods used. A reference ionisation chamber was 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 as illustrated in Figure 2. Measurements of charge collected with a reference ionisation chamber in both water and graphite phantoms were made, and corrected to standard conditions of temperature and pressure.

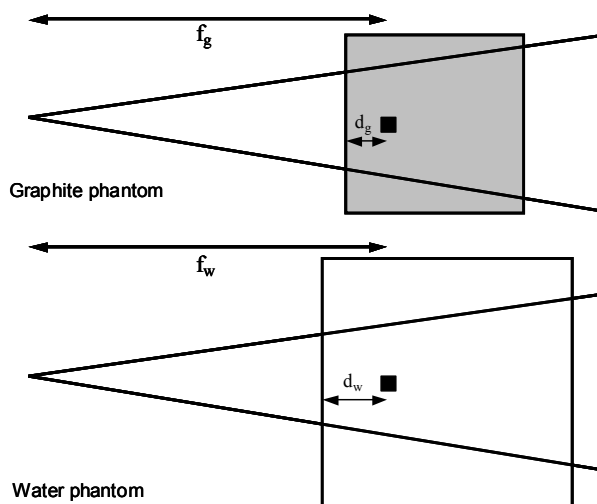


Figure 2. Scaled graphite and water phantoms used in the dose conversion. In the equidistant dose ratio method, the chamber measurement positions are located at a *same* distance from the source and at *scaled* depths in the phantoms. In this case the distances f_g and f_w were a constant SCD of 100cm. d_g and d_w were scaled by the inverse ratio of the electron densities of the phantom material.

In this work a source-to-chamber (SCD) of 100cm was used for all reported measurements. A small number of measurements were performed at other scaled SCDs, in each case ensuring the beam was fully enclosed by the water and graphite phantoms.

From the dimensions and densities of the plates that constitute the graphite phantom it was determined that the depth of the chamber measurement point from the front face of the graphite phantom was 5.603 g cm^{-2} for low-energy (4-10 MV) measurements, and 7.717 g cm^{-2} (15-25 MV) for high-energy measurements. These depths were fixed, as it was not possible to move the chamber within the graphite phantom, other than by adding graphite plates.

Two water phantoms were used for this work: a Perspex-walled phantom labelled phantom A, and a new calibration phantom of width 37.0 cm, length 31.0 cm and height 31.0 cm.

Phantom A is a cube of side 26.4 cm, with Perspex walls, with all dimensions approximately scaled in size to match the graphite phantom for electron density. The front face is 0.962 cm thick with a density of 1.18 g cm^{-3} , therefore equivalent to 1.135 g cm^{-2} of water. The additional depth of water required behind the Perspex front face to position the chamber at the equivalent scaled depth in water to that in the graphite phantom was 3.95 cm for the low energies and 5.85 cm for the high energies.

The calibration phantom is made of polycarbonate and has an entrance window of thickness 3.04 mm. The density of polycarbonate is 1.21 g cm^{-3} , therefore its mass thickness is 0.368 g cm^{-2} . A measurement bar to position the chamber at exactly 5.0 cm depth in water has been made, as this is the normal calibration depth for lower energies (4-10 MV). This bar has length 4.014 cm. For measurements made with this phantom the chambers were positioned at a water equivalent depth of 5.0 cm, therefore a small depth correction, $k_{\text{depth-conv}}$, was needed to correct the measurements to the scaled depth in graphite. For higher photon energies, of 15 MV and above, a second measurement bar of length 6.014 cm was used to position the chamber at a water equivalent depth of 7.0 cm. The correction $k_{\text{depth-conv}}$ is energy dependent due to the variation with energy of the dose gradient at the point of measurement, and due to the two different depths in water used at lower and higher energies.

The depth of measurement in water was scaled to be equivalent to the depth used in the graphite measurements, however the external dimensions of the calibration phantom were not scaled to those of the graphite phantom. Measurements with both phantoms under the same conditions confirmed that no correction was needed for the difference in scatter due to the different dimensions of the phantoms.

As for the calorimetry measurements, measurements of charge in both water and graphite were compared via the external PTW monitor chamber. The measurements were determined in the form of a charge per monitor reading, Q_g/Q_{mon} and Q_w/Q_{mon} , so that taking the ratio of measurements in graphite to those in water yields Q_g/Q_w , as required for the absorbed dose conversion in equation (4).

2.6 MODELLING REQUIREMENTS AND METHODS

Monte Carlo modelling is required at a number of stages in this work to determine absorbed dose to water at depth in a water phantom from measurements with the primary standard graphite calorimeter. In particular:

- a correction, k_{gap} , to account for the presence of non-graphite materials and air / vacuum gaps in the calorimeter,
- the ratio of dose to water to dose to graphite, D_w/D_g , in the phantoms (equidistant dose ratio method),
- a correction, k_{geom} , to account for the different geometrical configuration of the calorimeter and graphite chamber phantom.

In addition and prior to the calculation of this data, validated Monte Carlo source models of the NPL clinical linac are also required for each x-ray energy.

All the Monte Carlo simulations described in this work were performed using the EGSnrc code system (release V4-r2-2-5) (Kawrakow and Rogers 2006) together with the associated package BEAMnrc (release 2007) (Rogers *et al* 1995). Simulations were run on the NPL distributed computing grid that utilises the idle time of over 400 networked computers across the NPL site.

2.6.1 Clinical linac source models

BEAMnrc was first used to build an accurate model of the clinical linac source for each x-ray energy based on the manufacturer's specifications. The usercode DOSXYZnrc was then used to calculate central axis depth-dose and dose profiles for a 30x30 cm² field at different depths in a water phantom for each source (at 100cm SSD). The source configuration was fine-tuned by varying the energy of the incident electrons and spot-size on the target, and making small changes to specifications of the flattening filters (required for the higher x-ray energies) until agreement was obtained within suitable tolerances with ionisation chamber measurements in a large water filled plotting tank.

Further depth-dose and dose profile calculations were then performed for standard reference conditions (10x10 cm² field at 100cm and either 93 or 95 cm SSD) and compared with similar measurement data to verify that the tuned source models were also valid for this setup.

For the seven x-ray energies (after fine tuning each linac source), calculated depth-dose curves agreed with plotting tank measurement to better than 1% beyond the dose maximum ($d_{\max}$) for both 10x10cm² and 30x30cm² fields. Similarly, the calculated dose profiles agreed with measurement over the central region and 'horns' to within 1-2% at $d_{\max}$ and at various depths in the phantom although some small discrepancies in the regions beyond the penumbra have been observed. These small discrepancies, however, will have no significant effect on the dose values on axis under reference conditions that is of interest here. Penumbral widths of the profiles agree with measurements to within 1mm.

2.6.2 Calorimeter gap correction

A second usercode DOSRZnrc was used to build an accurate model of the primary standard graphite calorimeter that includes the air/vacuum gaps and major non-graphite materials present (Figure 3). The model consists of a small graphite core surrounded by a series of graphite jackets and phantom (shown in grey). The core and jackets are surrounded by evacuated gaps (white), to reduce heat losses in the measurements, and Perspex piping is also present as part of the vacuum system (diagonal shading). Graphite build-up plates (cross-hatch) are also used for all x-ray energies. A variable air gap is also present at the front of the calorimeter model.

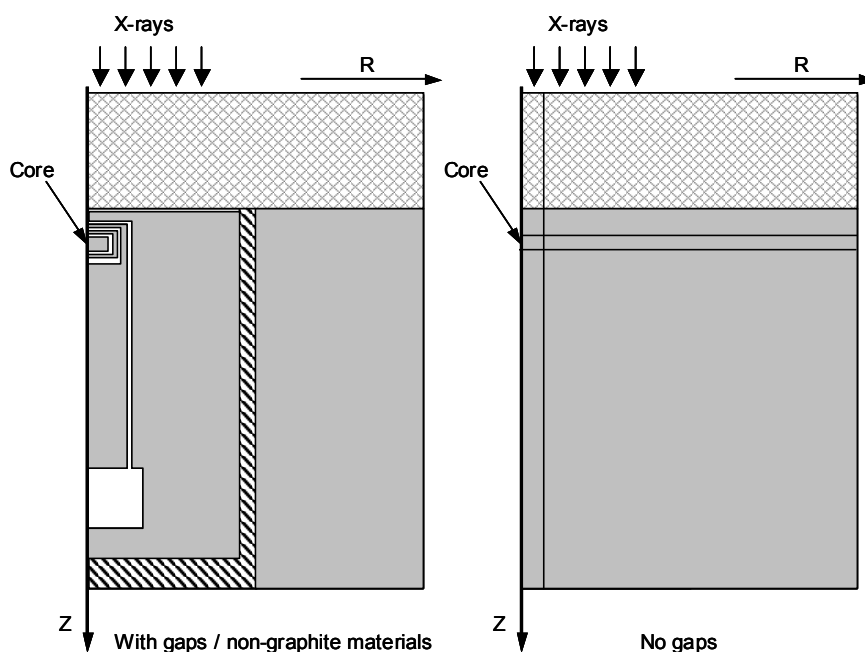


Figure 3. Calorimeter models with gaps and non-graphite materials (left), and without gaps and graphite only (right).

However we require dose to the core in homogeneous graphite so a second model of the calorimeter was also built with the gaps removed and non-graphite materials replaced with graphite ensuring that the mass-thickness of material upstream of the graphite core was unchanged (Figure 3).

Two simulations were then performed using these models for each x-ray energy to determine the dose to the calorimeter core with gaps and non-graphite materials, $D_{core-gaps}$, and without gaps, $D_{core-nogaps}$, under reference conditions (10x10 cm² field at 100 cm source-core distance). The ratio of these doses then gives the (compensated) gap correction, k_{gap} , that accounts for the presence of these components:

$$k_{gap} = \frac{D_{core-nogaps}}{D_{core-gaps}} \quad (7)$$

In each case, a full BEAM source simulation was used in DOSRZnrc using the validated clinical linac source models for each energy.

2.6.3 Geometry configuration (scatter) correction

To estimate the correction, k_{geom} , for the difference in scatter dose at the chamber measurement position due to the different geometrical configurations of the graphite phantom and calorimeter, a second model of the graphite phantom was built using DOSRZnrc (Figure 4).

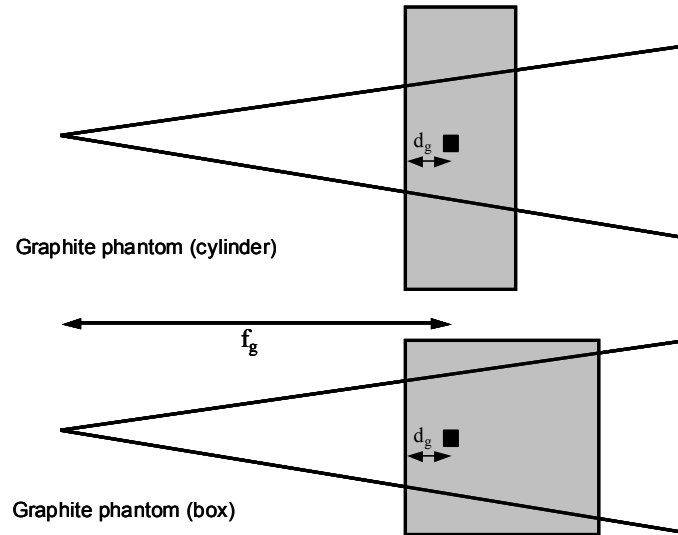


Figure 4. Graphite chamber phantom modelled: (top) as a cylinder with the same external dimensions as the calorimeter and equivalent thickness of material behind the core. and (bottom) as a standard box.

The phantom was modelled in detail but as a cylinder with the same external dimensions as the primary standard calorimeter, ensuring that the mass thickness of material behind the chamber measurement position was the same as that behind the calorimeter core. The dose, $D_{g,cyl}$, was then calculated in a 1 cm³ region at the chamber position using this model for each x-ray energy under reference conditions (10x10 cm² field at 100 cm source-core distance). The ratio of the dose, D_g , obtained with the standard box shaped graphite phantom under the same conditions to the dose, $D_{g,cyl}$, then gives the required correction:

$$k_{geom} = \frac{D_{g,ch}}{D_{g,cyl}} \quad (8)$$

Again a full BEAM source simulation was used in DOSRZnrc using the validated clinical linac source models. Checks were also made to ensure that both codes DOSXYZnrc and DOSRZnrc gave consistent results (within uncertainties) for similar equivalent models.

2.6.4 Graphite to water dose conversion

The user code DOSXYZnrc was used to model the scaled water and graphite phantoms used in the dose conversion measurements (equidistant dose ratio method). In particular, the individual graphite plates used to construct the phantom each of different density and thickness were modelled explicitly. The dose was calculated in a 1 cm³ region at the chamber measurement position at scaled depths in the water and graphite phantoms for a number of different source-chamber distances matching those used in the measurements (Figure 2). The required dose ratio, D_w/D_g , is then obtained from the ratio of these calculated doses.

Calculations were performed using a full BEAM source simulation for each x-ray energy using the validated clinical linac source models.

3 RESULTS

3.1 CALORIMETRY

A PTW transmission monitor chamber was used to transfer calorimeter measurements to the reference ionisation chambers, by calibrating the monitor in terms of absorbed dose to graphite at the position of the reference chamber. Two PTW monitor chambers were used at different times during this work. The calibration of each reference ionisation chamber was obtained as the absorbed dose to graphite, based on the transmission monitor reading, divided by the fully corrected reference chamber ionisation. The repeatability of monitor standard uncertainty on the each calorimeter measurement made over the course of each day was found to average 0.05%

The correction to the calorimeter dose to account for the difference in the depth of the calorimeter core and measurement point of the ionisation chamber in the graphite phantom, k_{depth} , is shown in Table 2. These results were measured for 6, 10 and 15 MV and are an estimate for the remaining energies. TPR measurements for these beams were determined at the time of commissioning the primary standards on the linac (Pearce and Bass 2010).

Table 2. The correction to the calorimeter dose to account for the difference in the depth of the calorimeter core and measurement point of the ionisation chamber in the graphite phantom.

Energy / MV	TPR	k_{depth}
4	0.633	0.9993
6	0.682	0.9993
8	0.713	0.9994
10	0.733	0.9995
15	0.758	0.9995
18	0.775	0.9995
25	0.800	0.9995

The standard uncertainty on the depth correction is estimated to be less than 0.1%.

3.2 ION RECOMBINATION

The correction due to ion recombination was determined using equation (9) (Burns and Rosser 1990) and applied to measurements made with the reference standard chambers. Table 3 lists the dose rates used and the calculated recombination corrections.

$$k_{ion} = 1.0014 + 0.23p \quad (9)$$

where p is the dose per pulse, in cGy.

Table 3. Beam parameters and ion recombination correction for each x-ray energy.

Energy / MV	TPR	Linac pulse repetition frequency (PRF) / Hz	Linac dose rate MU/minute	Ion recombination correction k_{ion}
4	0.633	400	249	1.0038
6	0.682	200	263	1.0065
8	0.713	200	293	1.0071
10	0.733	100	207	1.0096
15	0.758	100	219	1.0102
18	0.775	100	282	1.0124
25	0.800	100	250	1.0110

The standard uncertainty on the ion recombination correction is estimated to be less than 0.1%.

3.3 MONTE CARLO RESULTS

3.3.1 Calorimeter gap correction

Under reference conditions, the effect of gaps and non-graphite materials in the primary standard calorimeter was found to reduce the dose to the calorimeter core by between 0.6% (4 MV) and 0.2% (25 MV), as listed in Table 4 and plotted in Figure 5.

Table 4. Calculated gap corrections for the primary standard graphite calorimeter in x-ray beams from the NPL clinical linac.

Energy / MV	TPR	k_{gap}
4	0.633	1.0062
6	0.682	1.0050
8	0.713	1.0049
10	0.733	1.0031
15	0.758	1.0036
18	0.775	1.0023
25	0.800	1.0024

Also shown in figure 5 are the values originally measured by Owen and DuSautoy (1990) for the NPL clinical linac. The error bars indicate the estimated standard uncertainty in the k_{gap} correction of 0.14%.

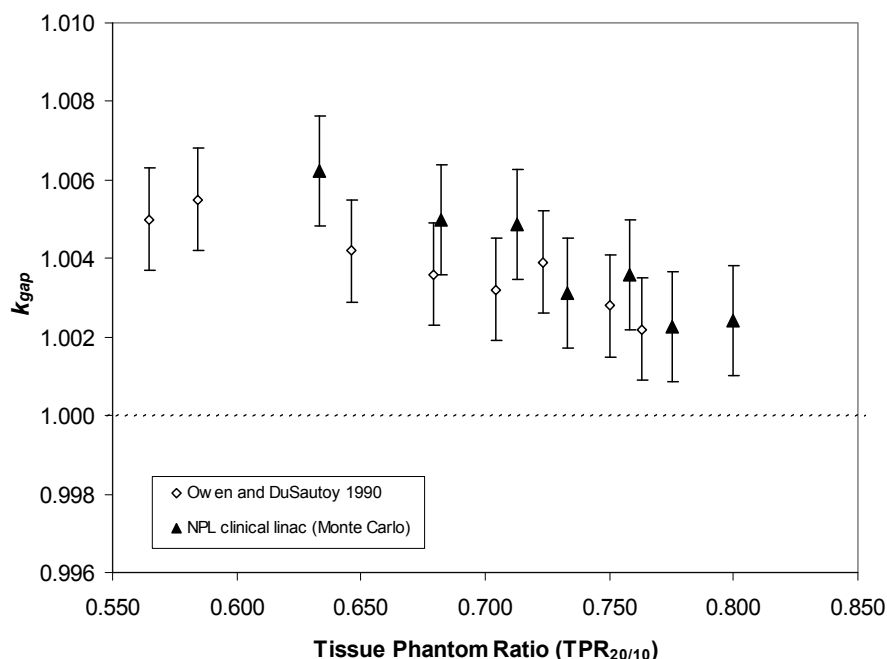


Figure 5. Comparison of gap corrections for the NPL primary standard graphite calorimeter calculated in this work and measured in earlier work (Owen and DuSautoy 1990).

3.3.2 Geometry configuration (scatter) correction

The correction to account for the change in scattered dose component at the chamber measurement position due to the different geometrical configuration of the primary standard calorimeter and graphite chamber phantom was calculated and is shown in Table 5.

These calculations were validated by making a series of ion chamber measurements using the graphite chamber phantom, in various configurations, at a few of the x-ray energies. The reduction in chamber response on moving slabs of graphite material from the back of the phantom to the side was found to be typically 0.1-0.2% and agreed with the Monte Carlo simulation results.

Table 5. The correction for changes in scatter due to the different geometry of the primary standard calorimeter and graphite phantom. The estimated standard uncertainty in this correction is 0.11%.

Energy / MV	TPR	k_{geom}
4	0.633	1.0019
6	0.682	1.0024
8	0.713	1.0021
10	0.733	1.0032
15	0.758	1.0001
18	0.775	1.0007
25	0.800	1.0000

3.3.3 Graphite to water dose conversion

Water-to-graphite dose ratios, D_w/D_g , in scaled phantoms, required for the photon fluence scaling-based dose conversion, were found to be mostly independent of source-chamber distance for energies 6, 10 and 15 MV. A number of distances, including 100 cm SCD but excluding the closest possible cases where backscatter into the monitor becomes significant, were investigated using Monte Carlo and consistent results found. Therefore for the remaining energies the ratio was determined only at 100 cm SCD, and using water phantom A. The ratio varied from 1.081 for 4MV X-rays to 1.115 for 25 MV x-rays, as shown in Table 6.

Measured values of the graphite-to-water charge ratio, Q_g/Q_w , are also shown in Table 6, for an SCD of 100 cm. The graphite-to-water charge ratios at 4, 8, 18 and 25MV include a small correction, $k_{depth-conv}$, to account for a small difference between the depth of measurement and the depth actually used in the Monte Carlo simulation.

Table 6. Ratios of measured charge and absorbed dose calibration factors in water and graphite. The values of D_w/D_g were determined using Monte Carlo simulations. The estimated standard uncertainty in N_w/N_g is 0.34%.

Energy / MV	TPR	$\frac{Q_g}{Q_w}$	$\frac{D_w}{D_g}$	$\frac{N_w}{N_g} = \frac{Q_g}{Q_w} \cdot \frac{D_w}{D_g}$
4	0.633	1.0495	1.0810	1.1345
6	0.682	1.0421	1.0903	1.1362
8	0.713	1.0392	1.0963	1.1393
10	0.733	1.0345	1.1001	1.1380
15	0.758	1.0368	1.1039	1.1446
18	0.775	1.0310	1.1066	1.1409
25	0.800	1.0260	1.1149	1.1438

The new data points are shown in Figure 6, together with curve fits determined previously (Nutbrown *et al* 2000 and Burns and Dale 1990). The associated uncertainties are shown at the beginning of each curve. Note that the UK standard as presently disseminated is still based on the Burns and Dale result, with which the new data agree most closely.

The solid points in Figure 6 were determined in a Philips SL15 linac by Nutbrown *et al* 2001. This linac is similar to the Elekta Synergy, and the results are in good agreement with the present work.

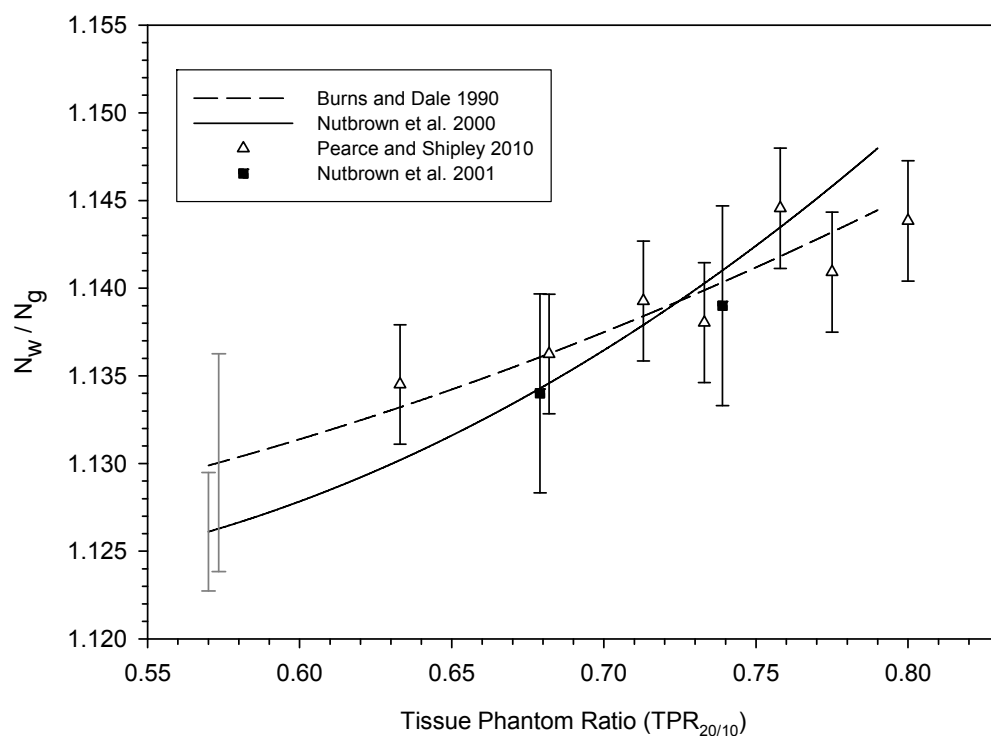


Figure 6. A plot of N_w/N_g as a function of tissue phantom ratio ($TPR_{20/10}$) for all MV X-ray energies for this work and in previous work. The estimated standard uncertainty is 0.34%.

3.4 DETERMINATION OF ABSORBED DOSE CALIBRATION FACTORS AND k_Q

The newly determined absorbed dose to water calibration factors for the reference ionisation chambers that were compared against the calorimeter are shown in Table 7. Dividing each value by the calibration factor in ^{60}Co γ -rays (in Table 8) gives the quality dependent correction, k_Q , for each chamber (Table 9), which has been averaged over the chambers (which are all of type 2611). The result is plotted in Figure 7 with the correction previously determined for beams produced by the NPL clinical linac. The combined standard uncertainty of k_Q is estimated to be 0.56%, for both the original curve and the new points, taking into account correlations in the various component uncertainties in this ratio of calibration factors.

Table 7. Measured absorbed dose to water calibration coefficients for the NPL reference chambers. The combined standard uncertainty associated with each calibration coefficient is 0.49%.^{**}

Energy MV	TPR	$N_w \text{ Gy/C} \times 10^7$						
		122	131	201	202	203	214	215
4	0.633	10.227	10.276	10.135	10.272	10.104	10.300	---
6	0.682	10.174	10.218	10.081	10.215	10.048	10.241	10.178
8	0.713	10.107	10.151	10.015	10.156	9.976	10.181	---
10	0.733	10.112	10.163	10.026	10.159	9.993	10.190	10.120
15	0.758	10.021	---	9.948	10.058	9.895	---	10.026
18	0.775	9.982	10.023	9.895	10.022	9.854	10.048	---
25	0.800	9.821	9.863	9.728	9.855	9.694	9.886	---

Table 8. Absorbed dose to water calibration coefficients for the NPL reference chambers in the reference quality.

Quality	TPR	$N_w \text{ Gy/C} \times 10^7$						
		122	131	201	202	203	214	215
^{60}Co	0.568	10.237	10.277	10.147	10.277	10.101	10.308	10.230

Table 9. Quality-dependent correction, k_Q , for the NPL reference chambers.

Energy MV	TPR	k_Q							
		122	131	201	202	203	214	215	Mean
4	0.633	0.9989	0.9999	0.9988	0.9995	1.0003	0.9992	---	0.9994
6	0.682	0.9938	0.9999	0.9935	0.9940	0.9947	0.9935	0.9949	0.9941
8	0.713	0.9872	0.9878	0.9870	0.9882	0.9876	0.9877	---	0.9876
10	0.733	0.9877	0.9889	0.9880	0.9885	0.9892	0.9886	0.9892	0.9886
15	0.758	0.9788	---	0.9804	0.9787	0.9795	---	0.9801	0.9795
18	0.775	0.9750	0.9753	0.9752	0.9752	0.9755	0.9747	---	0.9752
25	0.800	0.9593	0.9597	0.9587	0.9590	0.9597	0.9590	---	0.9592

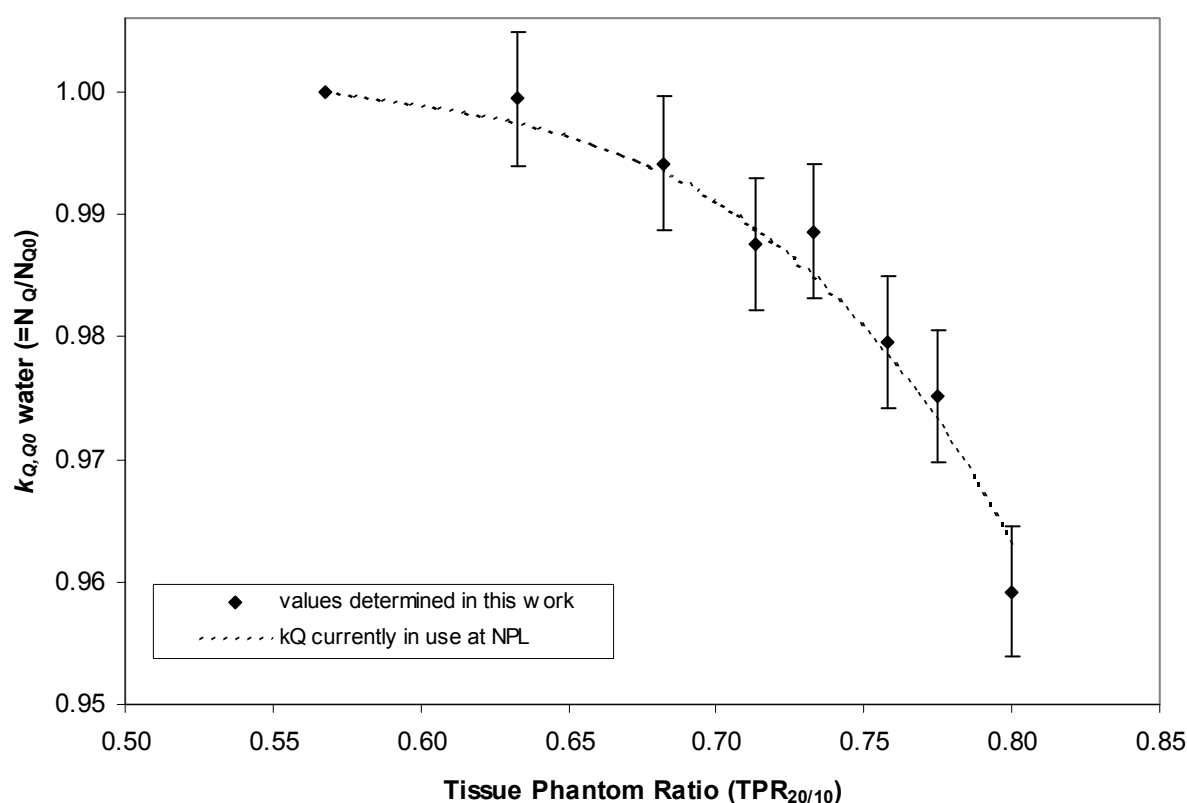


Figure 7. Absorbed dose to water in terms of k_Q as a function of Tissue Phantom Ratio (TPR_{20/10}). The standard uncertainty of k_Q is 0.56%, for the curve as well as for the new data.

One can define a quality dependent correction for the calibration in terms of absorbed dose to *graphite*, which eliminates the uncertainty associated with the dose conversion shown in Figure 6. The

new data are shown in Figure 8, together with the data points obtained from calorimetry in the NPL research linac beams. The dashed line is a fit to the research linac measurements and is evidently compatible with measurements in the NPL clinical linac. The standard uncertainty of this graphite k_Q is estimated to be 0.35%.

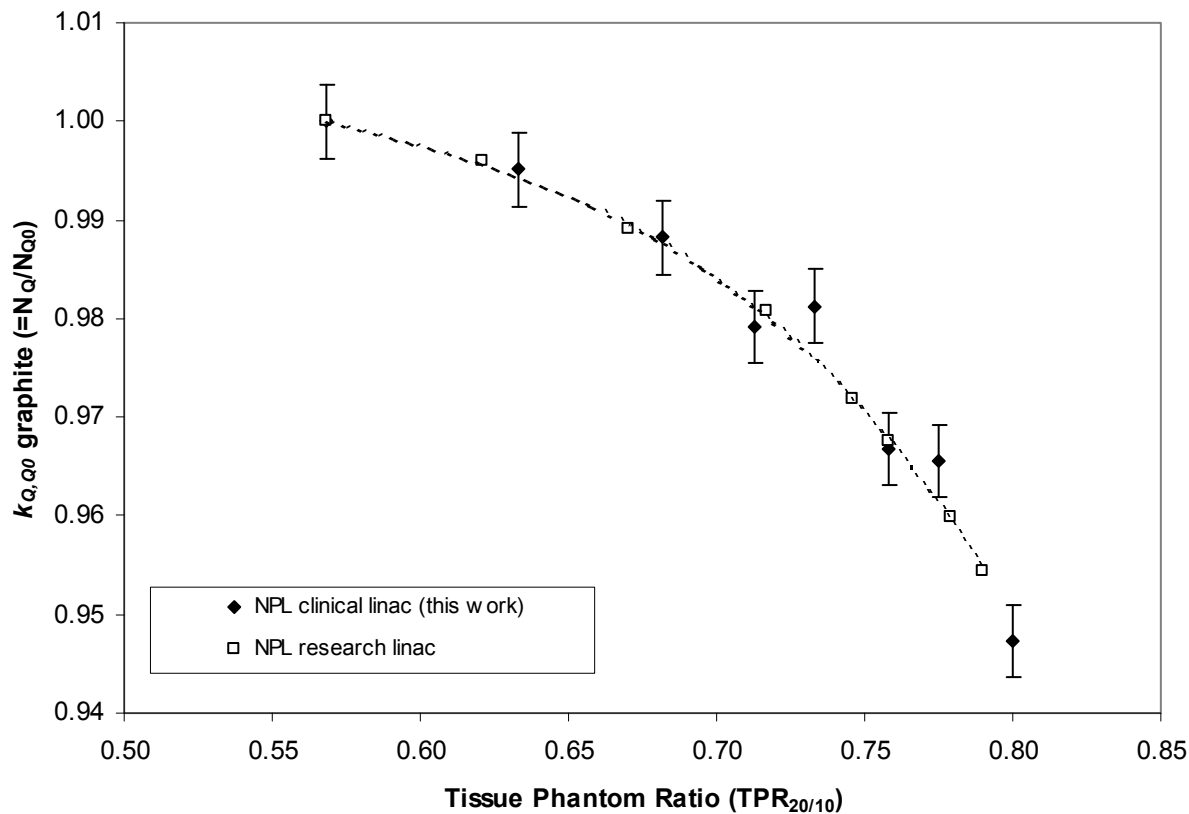


Figure 8. Quality dependent correction k_Q for absorbed dose to graphite, as a function of the beam quality index ($TPR_{20/10}$). The dashed curve is a fit to the NPL research linac data. The data shown is a comparison between that determined on the NPL research linac and that determined in this work on the clinical linac.

4 UNCERTAINTY

4.1 COMPONENT UNCERTAINTIES

The analysis of uncertainty here follows the ISO Guide to the Expression of Uncertainty in Measurement (1990). Uncertainties estimated statistically are grouped as type A and the rest are grouped as type B. These are added in quadrature to give a combined standard uncertainty with coverage factor $k=1$. The component uncertainties in the determination of N_w are presented in Table 10.

Table 10. Uncertainty budget for the calibration of one reference standard ionisation chamber in terms of absorbed dose to water on the NPL clinical linac. Component uncertainties are believed to have a Gaussian distribution, and sensitivity coefficients are all unity.

All standard uncertainties (%)	Type A (random)	Type B (non random)
calorimetry		
repeatability	0.05	-
lead loss	-	0.14
stray resistance	-	0.03
calorimeter corrections:		
heat transfer	-	0.10
mass	-	0.05
k_{gap}	0.10	0.10
k_{depth}	-	0.17
Sum of small corrections (including radial non-uniformity and distance from source), $\prod_i k_i$	-	0.10
realisation of absorbed dose to graphite, $D_{g,ch}$		
combining in quadrature	0.11	0.29
combined standard uncertainty	0.31	
ionisation measurement with one reference chamber, $Q_{g,ch}$		
repeatability	0.06	-
k_{geom}	0.10	0.05
electrometer calibration	-	0.05
air temperature	-	0.06
air pressure	-	0.05
humidity	-	0.10
recombination	-	0.03
calibration in absorbed dose to graphite (per reference standard), N_g		
combining in quadrature	0.16	0.32
combined standard uncertainty	0.36	
dose conversion		
Q_g/Q_w	0.20	0.10
D_w/D_g	0.15	0.20
$k_{depth-conv}$	-	0.05
combining in quadrature	0.25	0.23
combined std uncertainty (dose conv only)	0.34	
calibration in absorbed dose to water (per reference standard), N_w		
combining in quadrature	0.30	0.40
combined standard uncertainty	0.49	

4.2 REMARKS ON COMPONENT UNCERTAINTIES

Influence factors whose contribution to the standard uncertainty of N_w is less than 0.01% have been omitted from Table 10.

The standard deviation of calorimeter measurements over a few hours is typically 0.3%. One or two runs of 30-40 measurements can be completed in a day, leading to a standard deviation of the mean of 0.05%. This includes the effect of variations in linac output per PTW transmission monitor reading (no assumption is made about PTW monitor stability from one run to another). In those cases where calorimetry was repeated on different days, the rms difference between reference chamber calibration factors was found to average 0.08%, indicating that there is no significant additional contribution to the type A uncertainty beyond the short term repeatability quantified above. Previous estimates (DuSautoy 1996) of the uncertainties arising due to lead loss (0.14%), stray resistance (0.03%) and depth in graphite (0.17%) have been retained in the present analysis. The uncertainty in core mass was estimated at construction to be 0.05%. We estimate the additional uncertainty from remaining small corrections, $\prod_i k_i$, including the beam uniformity and correction for the distance from the source, to be 0.10%. Uncertainty due to the calibration of the digital voltmeters and the 5k Ω resistor were considered negligible and are not included in the uncertainty table.

The heat transfer correction arises because the effective temperature of jacket 1 seen by the core differs from the sensed value by an amount proportional to the power of the heater in jacket 1. The coefficient of proportionality was determined in purely electrical heating experiments by adjusting the temperature of jacket 2. (Even if the core and jacket 1 are kept at their usual set temperatures, the jacket 1 power required to do this is sensitive to the temperature of jacket 2.) The rate of heat loss by the core has a slight dependency on the heater of jacket 1. There remains a possible systematic effect because the heat transfer correction is determined under equilibrium conditions by varying jacket 2's temperature, whereas turning the beam on and off induces transient effects, the sum of which is assumed to be negligible. The uncertainty in the heat transfer correction was estimated to be 0.10%.

Measurements were analysed twice, using either the external PTW transmission monitor or the internal Elekta monitor. The former gives the better short-term reproducibility in absorbed dose per monitor unit, but the latter typically shows the smaller drift over the course of each day. A linear fit to output monitored by the PTW chamber over each day has been found to optimise the uncertainty in calibration of secondary standard chambers. In the present work, each run of calorimeter measurements was bracketed between initial and final measurements with the reference chambers, whose rms difference was 0.11%. The reference chamber calibration is based on the mean of initial and final measurements, which has a type A uncertainty of 0.06%.

The calculated correction for geometry configuration, k_{geom} , was found to be small and virtually negligible at the highest x-ray energies, which was confirmed in the experimental validation. The type A uncertainty (0.1%) arises from the statistics of the Monte Carlo simulations and the type B uncertainty is estimated to be 0.05%.

The type A uncertainty in k_{gap} arises from the SDOM in the calculations of $D_{core-gaps}$ and of $D_{core-nogaps}$, each typically 0.1% or better, added in quadrature. Small changes in the configuration of the source model at each energy were found not to change k_{gap} significantly. According to Owen and DuSautoy (1990), the uncertainty in total gap width in the calorimeter corresponds to an uncertainty of 0.07% in the gap correction in ^{60}Co γ -rays. A Type B uncertainty in k_{gap} of at most 0.1% is therefore considered appropriate in this work.

The type A uncertainty in the measured value of Q_g/Q_w was 0.2%, and we estimate a type B uncertainty of 0.10%. The value of D_w/D_g was determined only using the equidistant dose ratio method and shown to be independent of source-chamber distance (within 0.1%). The SDOM on the calculated dose values at all energies was typically 0.1% or better giving an estimated type A uncertainty of

0.15% when taken in quadrature. The dose ratio D_w/D_g is largely determined by the ratio of the mass-energy absorption coefficients in water and graphite and was found not to change significantly with small changes in the source configuration and beam energy. The value 0.2% for the type B uncertainty on the dose ratios is retained from earlier work (Nutbrown *et al.*, 2000) since the same arguments apply here.

The resulting combined standard uncertainty in the factor N_w/N_g required to convert the absorbed dose calibration from graphite to water is 0.34% ($k=1$).

The combined standard uncertainty in the calibration in terms of absorbed dose to water of one reference chamber, N_w , is 0.49% ($k=1$).

5 DISCUSSION

This study aimed to re-establish the absorbed dose primary standard for MV photon beams produced by the NPL Elekta clinical linac. In order that this could be achieved both measurements and validated Monte Carlo source models of the NPL clinical linac were required for each x-ray energy.

Among the measurement problems encountered were beam monitoring and linac drift, during both calorimetry and dose conversion measurements. Environment stability during calorimetry was particularly important; on a few occasions the calorimeter was found to be insufficiently stable or repeatable and those data were omitted from this analysis. The 8 MV (TPR 0.713) measurement only had one set of calorimetry measurements made and although these were the most stable of all datasets it will be important in future measurements to ensure that more than one day's measurements are available for analysis.

Ion recombination measurements determined using equation (9) were compared to measurements made previously using the two-voltage technique for a number of the available energies. There were no significant differences between the two methods.

Table 4 and Figure 5 show the correction required for the presence of gaps and no-graphite materials within the calorimeter. These corrections are consistent with earlier experimental investigations of this correction carried out on the existing NPL research linac using similar x-ray beams with comparable radiation qualities (TPRs) (Owen and DuSautoy, 1990). One should note that the earlier work only considered the effect of the gaps close to the calorimeter core and also did not attempt to determine the effect of non-graphite materials. Although these effects are not expected to be large, they may explain why the values determined in this work appear to be very slightly higher.

The change in the scattered dose component at the chamber measurement position due to the different geometrical configuration of the primary standard calorimeter and graphite phantom were found to be 0.3% or less at the lower x-ray energies and negligible at energies above 10 MV (Table 4). As one would expect, the increase in backscatter is greater than the reduction in side scatter, and the effect is more significant at lower energies.

The Monte Carlo calculated water-to-graphite dose ratio, D_w/D_g , in scaled phantoms varied from 1.081 for 4MV X-rays to 1.115 for 25MV X-rays and was consistent with dose ratios previously calculated for both lightly and heavily filtered beams on the NPL research linac (Nutbrown *et al.* 2000).

One of the largest sources of uncertainty in this work is the measured graphite-to-water charge ratio Q_g/Q_w . These measurements are particularly sensitive to setup errors. For example, the sensitivity coefficient for the contribution to the ratio N_w/N_g from water measurement depth is typically 0.6%/mm. The sensitivity to SCD is less marked (0.2%/mm) but particular care was taken during setup and to check metrology during the measurements.

Figure 6 illustrates that there is generally very good agreement between the graphite-to-water dose conversion factors determined in this work to and those determined previously in the NPL research linac (Nutbrown *et al* 2000), as well as those of Burns and Dale 1990, which are incorporated into the standard as presently disseminated. Since the equidistant and scaled dose ratio methods previously gave equivalent results, and the equidistant method eliminates uncertainty arising from the virtual source position, that method was adopted here. The agreement with previous measurements in a Philips SL15 clinical linac (Nutbrown *et al* 2001) is reassuring.

The dashed line in Figure 7 illustrates the fit to the original k_Q data determined on the NPL research linac, currently in use. It can be seen in the figure that the new k_Q points are generally consistent with the existing k_Q curve and are typically within 0.3% of the curve. The error bars shown indicate a standard uncertainty for the 2611 calibration of 0.56%, and all points are well within this uncertainty. The chamber-to-chamber spread at each point is entirely determined by the reproducibility of chamber measurements and so is typically 0.1%. The uncertainty of k_Q is much larger, since it includes the uncertainty of calorimetry.

Figure 8 shows the comparison between old and current k_Q in terms of absorbed dose to graphite, with good agreement. The apparent increase in k_Q from 8MV to 10 MV is assumed to reflect measurement uncertainty rather than a real effect due, for example, to very different beam filtrations. This uncertainty will improve as more calorimetry data become available for analysis.

The curve fit to k_Q data determined previously at NPL has an rms residual for those data of only 0.03%. The rms deviation of the new values from this curve is much larger (0.26%), but still compatible with the estimated uncertainty (0.56%). The fact that there is no systematic trend in the residuals justifies the continued dissemination of calibrations based on the existing k_Q curve with the original estimate of standard uncertainty (0.7% instead of the 0.5% in this work).

6 CONCLUSIONS

Absorbed dose to water has been determined in the x-ray beams from the NPL clinical linac, via two routes traceable to the NPL primary standard. The first route gives the standard as currently disseminated, which is based on interpolation of the existing reference standard chamber calibration, determined from calorimetry and dose conversion in the research linac beams, as a function of beam quality index, $TPR_{20/10}$. The second is based on calorimetry and dose conversion in the clinical linac beams. The direct determination is completely consistent with that based on interpolation: the difference shows no systematic trend with quality index and is comfortably within the estimated uncertainty.

Given that the development of a new calorimeter to replace the existing primary standard is nearing completion, and given users' understandable preference to avoid unnecessary changes in the standard, it has been decided that the disseminated standard should continue to be that based on interpolation, at least until the new calorimeter is fully commissioned as a primary standard.

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