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THE NPL ABSORBED DOSE TO WATER PRIMARY STANDARD FOR ELECTRON BEAMS: SUMMARY OF FACTORS INCORPORATING ICRU REPORT 90 RECOMMENDATIONS

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The NPL absorbed dose to water primary standard for electron beams: summary of factors incorporating ICRU Report 90 recommendations

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ABSTRACT
The NPL absorbed dose to water primary standard calorimeter for therapy level electron beam qualities was established in the 1990s. The correction factors applicable to the primary standard have been reviewed or reassessed, incorporating recommendations from the International Commission for Radiation Measurements and Units Report 90. This report summarises all the factors.

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CONTENTS

1 INTRODUCTION

In the 1990s the therapy level electron absorbed dose primary standard calorimeter was established at NPL and an associated measurement service offered for the routine calibration of secondary standard ionisation chambers (Burns *et al.* 1994, McEwen *et al.* 1998). A programme of work began in December 2014 to re-evaluate the correction factors for the primary standard. The recommendations of ICRU Report 90 (ICRU, 2016) were also addressed.

This report summarises the correction factors applicable to the primary standard resulting from the re-evaluation.

2 CALORIMETER SYSTEM

2.1 PRINCIPAL OF OPERATION

The energy J (in joules, J) absorbed by an irradiated body of mass m (in kg) can be related to the measured temperature rise Δt (in Celsius, C) and the specific heat capacity c of the material (in joules per kg per kelvin, J/kg/°C) by the relationship

$$J = m \cdot c \cdot \Delta t$$

By definition, the absorbed dose D in J/kg is therefore simply

$$D = c \cdot \Delta t$$

The mass of the absorber is not required if, as in this case, its specific heat capacity is known. Williams *et al.* characterised the specific heat capacity for samples of the graphite used to manufacture the calorimeter.

2.2 CONSTRUCTION

The main calorimeter body comprises a graphite absorber (the calorimeter 'core') with graphite surrounding pieces. The core is a disc 50 mm in diameter and 2 mm thick. The thickness of the core is 0.3490 g cm^{-2}. Two holes are drilled into the edge of the disc to accommodate two bead thermistors of resistance 25 kΩ at 22°C, diameter 0.5 mm and length 3 mm.

2.3 MEASUREMENT SYSTEM

Each core thermistor is included in one arm of a dedicated DC Wheatstone bridge. A commercial digital nanovoltmeter reads the out-of-balance voltages from the Wheatstone bridges. The out-of-balance voltage was calibrated against temperature in Celsius using a calibrated PRT thermometer.

2.4 ANALYSIS

The temperature of thermistor/bridge 1 is calculated from the out-of-balance voltage using the equation below:

$$T = a3 \cdot V^3 + a2 \cdot V^2 + a1 \cdot V + a0$$

where

T is the temperature, °C
V is the bridge 1 out-of-balance voltage, V
$a3$ is a constant of value 0.04211792 °C/V^3
$a2$ is a constant of value 0.05660155 °C/V^2
$a1$ is a constant of value 6.41269533 °C/V^1
$a0$ is a constant of value 22.1411253 °C.

3 ELECTRON BEAM QUALITIES

3.1 DEFINITION OF ELECTRON BEAM QUALITY SPECIFIER

The beam quality specifier for electron beams is taken to be $R_{50,Dw}$ (IPEM 2003). This is the depth on the central axis in water (in cm) at which the dose is 50% of the maximum value.

The calibration in water is performed at the reference depth $z_{\mathrm{ref,w}}$ cm calculated from

$$z_{\mathrm{ref,w}} = 0.6 \cdot R_{50,Dw} - 0.1$$

The reference depth in graphite $z_{\mathrm{ref,g}}$ is given by

$$z_{\mathrm{ref,g}} = z_{\mathrm{ref,w}} \cdot \frac{R_{50,Dg}}{R_{50,Dw}}$$

where

$R_{50,Dg}$ is the depth in graphite at which the dose is 50% of the maximum value.

3.2 REFERENCE DEPTHS FOR ELEKTA SYNERGY CLINICAL LINAC

A combination of depth ionisation measurements and beam modelling in water and graphite for each beam energy yielded reference depths in water (Table 1) and graphite (Table 2).

Table 1 Reference depths in water for the Elekta Synergy clinical linac

Beam energy MeV	$R_{50,Dw}$ gcm^{-2}	$z_{\mathrm{ref,w}}$ gcm^{-2}
4	1.65	0.89
6	2.36	1.32
10	4.11	2.37
12	4.81	2.79
15	5.90	3.45
20	8.14	4.80

Table 2 Reference depths in graphite for the Elekta Synergy clinical linac

Beam energy MeV	$R_{50,Dg}$ gcm^{-2}	$z_{\mathrm{ref,g}}$ cm
4	1.09	0.59
6	1.54	0.86
10	2.67	1.54
12	3.14	1.82
15	3.91	2.29
20	5.29	3.12

3.3 CALORIMETER MEASUREMENT EQUATION FOR DOSE TO GRAPHITE

The fully-corrected dose to graphite D_g is calculated from the following equation:

$$D_g = c_g \cdot \Delta t \cdot k_{cal}$$

where

c_g is the specific heat capacity of the core graphite (J/kg/°C), calculated from the temperature T °C at the time of measurement (Williams *et al.*):

$$c_g = 644.9 + 2.44T$$

Δt is the temperature rise (°C) from an irradiation, typically 200 MU, calculated from the measured change in bridge voltage

k_{cal} is the total correction factor to be applied to the calorimeter response, given by

$$k_{cal} = k_{back} \cdot k_{core} \cdot k_{depth} \cdot k_{dist} \cdot k_{gap} \cdot k_{heat} \cdot k_{mat} \cdot k_{scat} \cdot k_{unif}$$

where

k_{back} is a factor for the lack of backscatter in the calorimeter phantom.

k_{core} is a factor to correct for the averaging of the dose distribution across the core depth.

k_{depth} is a factor to correct for the deviation of the depth of measurement of the core in the graphite phantom from the reference position, calculated from the depth dose data.

k_{dist} is a factor to correct for any deviation of the measurement point from the reference distance from the source. The front surfaces of the calorimeter and chamber phantom are both aligned to the sagittal laser in the linac exposure room. The correction is taken to be unity with an associated uncertainty.

k_{gap} is a factor to correct for the effect of the air gap around the core of the calorimeter. Kirby (2007) modelled the calorimeter to investigate this effect and concluded that the correction is unity.

k_{heat} is a factor to correct for the heat defect of graphite. This is assumed to be negligible for graphite.

k_{mat} is a factor to correct for the presence of impurities in the core. This is taken to be negligible for this calorimeter.

k_{scat} is a factor to correct for the calorimeter phantom being of finite size and therefore the scatter is different from the case for a semi-infinite phantom. The factor is taken to be unity.

k_{unif} is a factor to correct for the non-uniformity of the beam. Beam profile measurements were performed in water at the reference depth for each energy with the 14×14 cm applicator fitted. The factor corrects the average of the beam profile over an area equivalent to the core to a point on the central axis.

3.4 SUMMARY OF CORRECTION FACTORS TO CALORIMETER RESPONSE

Table 3 gives the correction factors applicable to the calorimeter response.

Table 3 Summary of correction factors to calorimeter response

Energy MeV	$z_{ref,g}$ gcm^{-2}	Correction factors to calorimeter response									Total
		k_{back}	k_{core}	k_{depth}	k_{dist}	k_{gap}	k_{heat}	k_{mat}	k_{scat}	k_{unif}	k_{cal}
4	0.59	1.0042	1.0058	1.0008	1.0000	1.0000	1.0000	1.0000	1.0000	1.0005	1.0114
6	0.86	1.0064	1.0023	0.9995	1.0000	1.0000	1.0000	1.0000	1.0000	1.0003	1.0085
10	1.54	1.0011	1.0007	0.9996	1.0000	1.0000	1.0000	1.0000	1.0000	1.0008	1.0022
12	1.82	1.0007	1.0006	1.0013	1.0000	1.0000	1.0000	1.0000	1.0000	1.0009	1.0034
15	2.29	1.0014	1.0005	1.0048	1.0000	1.0000	1.0000	1.0000	1.0000	1.0010	1.0077
20	3.12	1.0020	1.0001	1.0023	1.0000	1.0000	1.0000	1.0000	1.0000	1.0024	1.0069

4 IONISATION CHAMBER CALIBRATION IN TERMS OF DOSE TO GRAPHITE

The transfer standard ionisation chambers are currently calibrated against the primary standard calorimeter by measuring their response in a graphite phantom and comparing it to the dose measured by the calorimeter for the same MU delivered:

$$N_{D,g} = \frac{D_g/MU}{Q_{cham}/MU}$$

4.1 MEASUREMENT EQUATION FOR IONISATION CHAMBER CHARGE

The fully-corrected ionisation chamber charge Q_{cham} is calculated from the following equation:

$$Q_{cham} = Q_{raw} \cdot k_{meas} \cdot k_{set\ up}$$

where

Q_{raw} is the raw measured charge reading displayed on the electrometer for a known delivered dose, typically 200 MU.

k_{meas} is the total correction factor to be applied to the ionisation chamber response for influence factors established at the time of measurement, given by

$$k_{meas} = k_{elec} \cdot k_{ion} \cdot k_{non-lin} \cdot k_{pol} \cdot k_{TP}$$

where

k_{elec} is a factor to account for the electrometer range sensitivity.

k_{ion} is a factor to account for the ion-pair recombination effect in the ionisation chamber.

$k_{non-lin}$ is a factor to account for the electrometer range non-linearity.

k_{pol} is a factor to account for the polarity effect in the ionisation chamber.

k_{TP} is a factor to account for the difference in the air density in the ionisation chamber from reference conditions (20 C and 1013.25 mBar).

$k_{set\ up}$ is the total correction factor to be applied to the ionisation chamber response for routine set up-related influence factors, given by

$$k_{set\ up} = k_{back,ch} \cdot k_{depth,ch} \cdot k_{dist,ch} \cdot k_{scat,ch} \cdot k_{unif,ch}$$

where

$k_{back,ch}$ is a factor for the lack of backscatter in the chamber phantom. Full backscatter conditions are used here. The factor is taken to be unity.

$k_{depth,ch}$ is a factor to correct for the deviation of the depth of measurement of the chamber reference point in the graphite phantom from the reference position, calculated from the depth dose data.

$k_{dist,ch}$ is a factor to correct for any deviation of the measurement point from the reference distance from the source. The front surfaces of the calorimeter and chamber phantom are both aligned to the sagittal laser in the linac exposure room. The correction is taken to be unity with an associated uncertainty.

$k_{scat,ch}$ is a factor to correct for the chamber phantom being of finite size and therefore the scatter is different from the case for a semi-infinite phantom. The factor is taken to be unity.

$k_{unif,ch}$ is a factor to correct for the non-uniformity of the beam. Beam profile measurements were performed in water at the reference depth for each energy with the 14×14 cm applicator fitted. The factor corrects the average of the beam profile over an area equivalent to the chamber to a point on the central axis.

4.2 SUMMARY OF CORRECTION FACTORS TO MEASURED CHARGE DEPENDENT ON SET-UP ONLY

Values for correction factors applicable to chamber charge measurements related to the set-up are summarised in Table 4.

Table 4 Summary of correction factors to measured charge dependent on set-up only

Energy MeV	$z_{\mathrm{ref,g}}$ gcm^{-2}	Correction factors to measured charge					Total
		$k_{back,ch}$	$k_{depth,ch}$	$k_{dist,ch}$	$k_{scat,ch}$	$k_{unif,ch}$	$k_{set\ up}$
4	0.59	1.0000	1.0007	1.0000	1.0000	1.0002	1.0009
6	0.86	1.0000	0.9995	1.0000	1.0000	0.9999	0.9994
10	1.54	1.0000	1.0002	1.0000	1.0000	1.0001	1.0002
12	1.82	1.0000	1.0013	1.0000	1.0000	1.0000	1.0013
15	2.29	1.0000	1.0050	1.0000	1.0000	1.0000	1.0050
20	3.12	1.0000	1.0020	1.0000	1.0000	1.0004	1.0024

5 CONVERSION FROM DOSE TO GRAPHITE TO DOSE TO WATER

The calibration of a transfer standard ionisation chamber against the primary standard yields an absorbed dose to graphite calibration coefficient $N_{D,g}$. The absorbed dose to water calibration coefficient $N_{D,w}$ is calculated by

$$N_{D,w} = N_{D,g} \cdot F_{g\ to\ w}$$

where

$$F_{g\ to\ w} = \frac{p_w}{p_g} \cdot \frac{s_{w/air}}{s_{g/air}}$$

and

p_w is the perturbation correction for the presence of the chamber in water
p_g is the perturbation correction for the presence of the chamber in graphite
$s_{w/air}$ is the stopping power ratio water to air
$s_{g/air}$ is the stopping power ratio graphite to air.

5.1 PERTURBATION CORRECTION

The perturbation correction ratio p_w/p_g has been taken to be unity (Burns *et al.* 1994, McEwen *et al.* 1998) with a large associated uncertainty since the beginning of the calibration service. Bailey *et al.* (2015) modelled the Elekta linac electron beams and transfer chambers to provide a formula for calculating perturbation correction factors in a water phantom for the PTW Roos and NACP-02 type chambers over the full PDD range for each energy. The formula was used to calculate p_w factors for the transfer chambers at z_{ref} in water. The same models were used by Barry *et al.* (2023) to calculate corresponding perturbation corrections at z_{ref} in graphite incorporating recommendations from the International Commission for Radiation Measurements and Units (ICRU) Report 90 (ICRU, 2016). Table 5 gives the perturbation values in water and graphite and the ratio p_w/p_g, represented graphically in Figure 1.

Table 5 Perturbation correction factors for the PTW Roos transfer standard chambers

Energy MeV	$R_{50,Dw}$ cm	PTW Roos		
		p_w	p_g	p_w/p_g
4	1.65	1.0181	1.0125	1.0055
6	2.36	1.0144	1.0115	1.0029
10	4.11	1.0092	1.0089	1.0002
12	4.81	1.0078	1.0090	0.9988
15	5.90	1.0066	1.0089	0.9978
20	8.14	1.0068	1.0100	0.9969

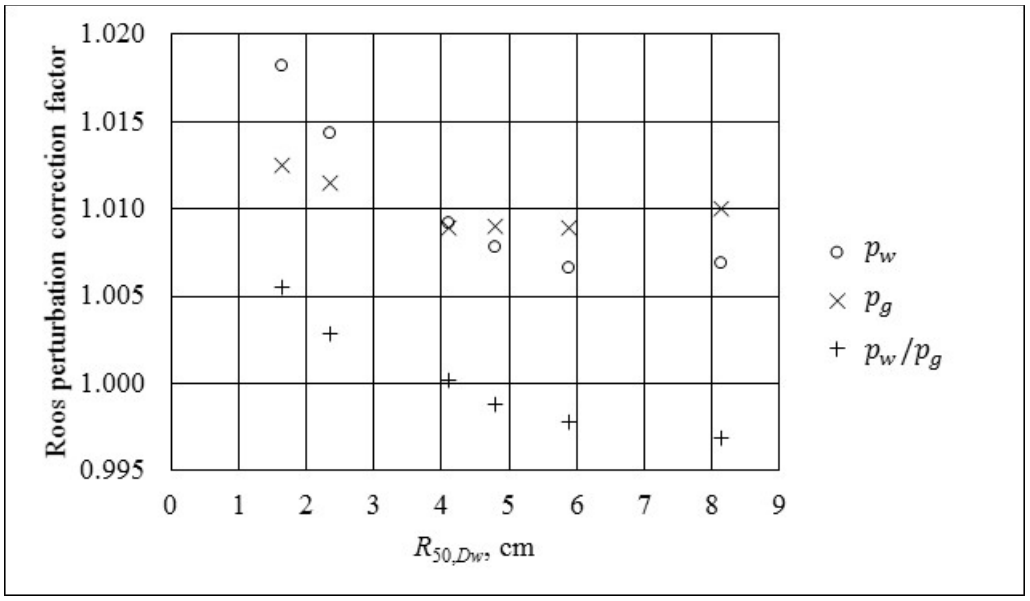

Figure 1 Perturbation correction factors for the PTW Roos transfer standard chambers

5.2 STOPPING POWER RATIO

The stopping power ratios water to air ($s_{w/air}$) and graphite to air ($s_{g/air}$) were calculated by Shipley and Barry (2019) for PTW Roos chambers in accordance with ICRU Report 90 (2016). Values for $s_{w/air}$, $s_{g/air}$ and the ratio of stopping power ratios $\frac{s_{w/air}}{s_{g/air}}$ are given in Table 6, represented graphically in Figure 2 and Figure 3.

Table 6 Stopping power ratios

Energy MeV	$R_{50,Dw}$ cm	$s_{w/air}$	$s_{g/air}$	$\frac{s_{w/air}}{s_{g/air}}$
4	1.65	1.0860	0.9456	1.1485
6	2.36	1.0733	0.9349	1.1480
10	4.11	1.0501	0.9164	1.1459
12	4.81	1.0436	0.9114	1.1451
15	5.90	1.0357	0.9034	1.1465
20	8.14	1.0208	0.8931	1.1430

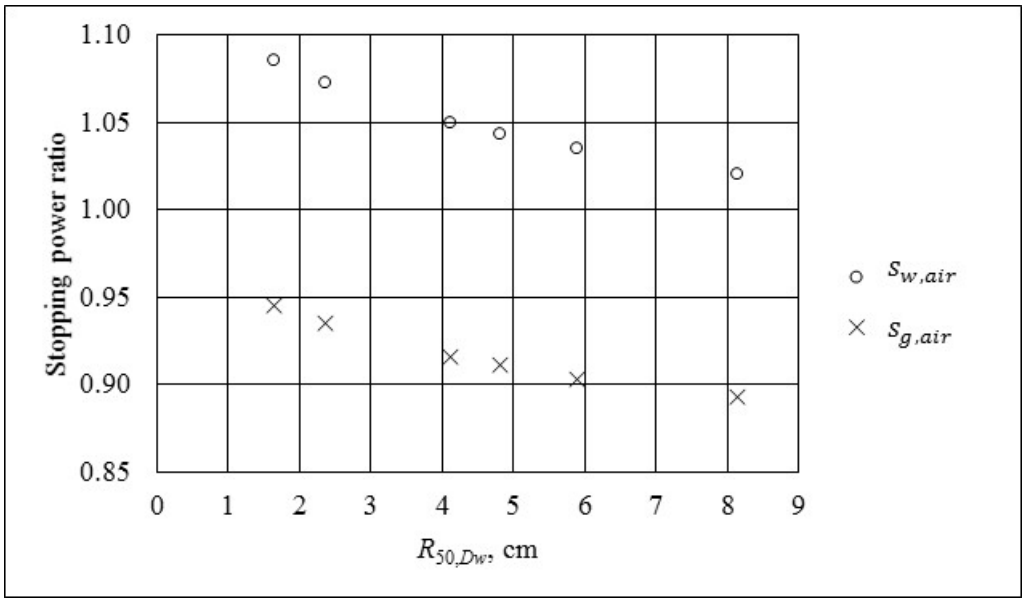

Figure 2 Stopping power ratios

5.3 TOTAL FACTOR TO CONVERT FROM DOSE TO GRAPHITE TO DOSE TO WATER

Table 7 gives (i) the Roos perturbation ratio water to graphite $\frac{p_w}{p_g}$, (ii) the ratio of stopping power ratios $\frac{s_{w/air}}{s_{g/air}}$ and the product of (i) and (ii) to result in the total factor $F_{g\ to\ w}$ to convert the Roos transfer chamber dose to graphite sensitivity $N_{D,g}$ to dose to water sensitivity $N_{D,w}$ (grays per coulomb). The 'fit' values are calculated from a binomial fit to $F_{g\ to\ w}$:

$$F_{g\ to\ w} = 1.1614 - 0.004679 \cdot R_{50,Dw} + 0.0002481 \cdot (R_{50,Dw})^2$$

This equation will be used to recalculate values of $F_{g\ to\ w}$ following remeasurement of beam quality, if necessary. Figure 3 shows $\frac{s_{w/air}}{s_{g/air}}$ and $F_{g\ to\ w}$.

Table 7 Total factor $F_{g\ to\ w}$ to convert Roos sensitivity from dose to graphite to dose to water

Energy MeV	$R_{50,Dw}$ cm	$\frac{p_w}{p_g}$	$\frac{s_{w/air}}{s_{g/air}}$	$F_{g\ to\ w}$ (raw)	$F_{g\ to\ w}$ (fit)
4	1.65	1.0055	1.1485	1.1549	1.1544
6	2.36	1.0029	1.1480	1.1513	1.1517
10	4.11	1.0002	1.1459	1.1461	1.1464
12	4.81	0.9988	1.1451	1.1437	1.1449
15	5.90	0.9985	1.1466	1.1449	1.1432
20	8.14	0.9988	1.1431	1.1417	1.1421

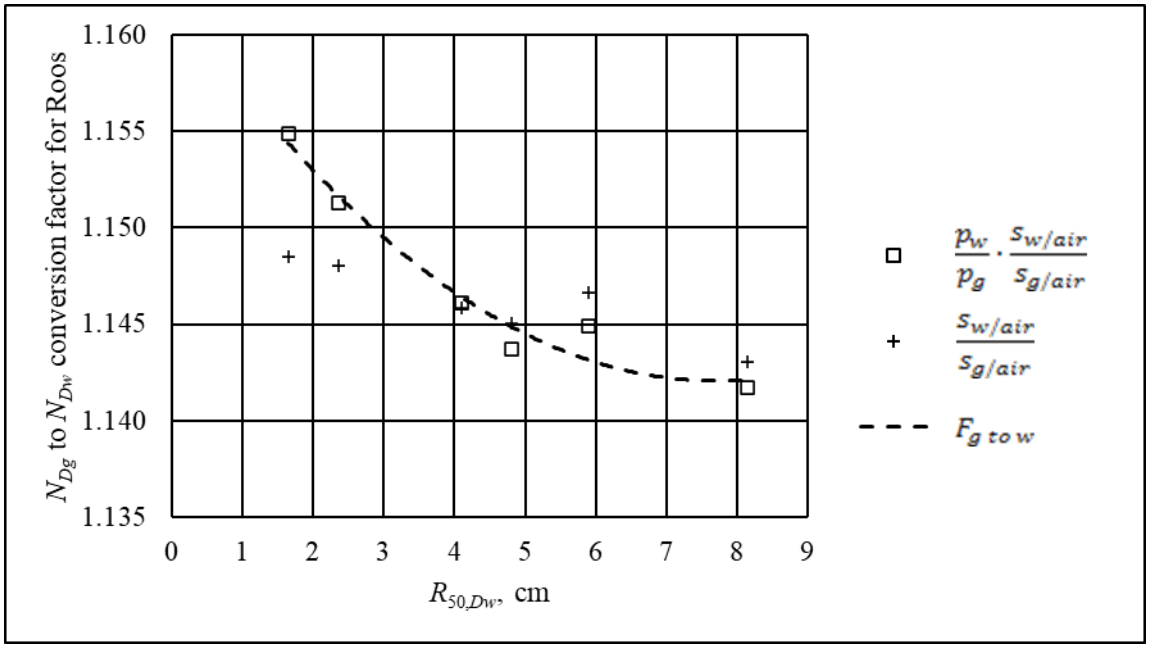

Figure 3 Total conversion factor $F_{g\ to\ w}$

6 CHANGES TO THE PRIMARY STANDARD DUE TO RE-EVALUATION

The total changes to the electron primary standard realisation of absorbed dose resulted from

(i) the re-evaluation of existing factors
(ii) the recalculation of stopping power ratios in accordance with ICRU Report 90
(iii) the introduction of calculated perturbation ratios
(iv) analysis of calorimetry and ionisation chamber measurements in the clinical linac electron beams at NPL during 2015-2019.

The changes, effective from 1st of September 2019, are given in Table 8. NPL Report IR 55 (Bass *et al.* 2019) similarly summarises the total changes to the UK primary standards of air kerma and absorbed dose, and the resulting effect on calibration coefficients of secondary standard ionisation chambers calibrated at NPL. Please note that the beam qualities are slightly different to those listed elsewhere in this report.

Table 8 Total changes to the electron beam primary standard realisation of absorbed dose

Nominal energy (MeV)	$R_{50,D}$ (cm)	$\frac{\text{1st September 2019}}{\text{Pre 1st of September 2019}}$
4	1.54	1.016
6	2.30	1.013
10	3.90	1.007
12	4.58	1.005
15	5.75	1.001
20	7.83	0.997

7 UNCERTAINTIES

7.1 UNCERTAINTIES IN THE PRIMARY STANDARD

Table 9 Uncertainties in the primary standard

Symbol	Quantity, source of uncertainty	Type A	Type B
c_g	Specific heat capacity of the core graphite	-	0.16
T	Calibration of core thermistor	-	0.05
k_{back}	Factor for the lack of backscatter in the calorimeter phantom	-	0.25
k_{core}	Factor to correct for the averaging of the dose distribution across the core depth	-	0.05
k_{depth}	Factor to correct for the deviation of the depth of measurement of the core in the graphite phantom from the reference position	-	0.10
k_{dist}	Factor to correct for any deviation of the measurement point from the reference distance from the source	-	0.10
k_{gap}	Factor to correct for the effect of the air gap around the core of the calorimeter	-	0.17
k_{heat}	Factor to correct for the heat defect of graphite	-	0.10
k_{mat}	Factor to correct for the presence of impurities in the core	-	0.05
k_{scat}	Factor to correct for the calorimeter phantom being of finite size and therefore the scatter is different from the case for a semi-infinite phantom	-	0.05
k_{unif}	Factor to correct for the radial non-uniformity of the beam	-	0.05
$u_c(k_{cal})$	Combined standard uncertainty	0.40	

7.2 UNCERTAINTIES IN THE PRIMARY STANDARD MEASUREMENT (DOSE PER LINAC MONITOR UNIT)

Table 10 Uncertainties in the primary standard measurement (dose per linac monitor unit)

Symbol	Quantity, source of uncertainty	Type A	Type B
k_{cal}	Total primary standard correction	-	0.40
V	Nanovoltmeter calibrated with the thermistor as a system	0.05	-
R	Repeatability (includes fits to data)	0.15	-
$u_c(D_g/MU)$	Combined standard uncertainty	0.43	

7.3 UNCERTAINTIES IN THE CALIBRATION OF A PTW ROOS TRANSFER STANDARD (DOSE TO GRAPHITE)

Table 11 Uncertainties in the calibration of a PTW Roos transfer standard (dose to graphite)

Symbol	Quantity, source of uncertainty	Type A	Type B
D_g/MU	Dose to graphite per monitor unit	-	0.43
k_{elec}	Electrometer charge calibration (nC/'nC')	-	0.06
k_{ion}	Ion recombination correction	0.05	-
k_{pol}	Polarity effect correction	0.05	-
$I_{leakage}$	Leakage current (A)	0.05	-
P	Pressure (kPa)	0.02	-
T	Temperature (K)	0.01	-
$k_{depth,ch}$	Factor to correct for the deviation of the depth of measurement of the chamber in the graphite phantom from the reference position	-	0.10
$k_{dist,ch}$	Factor to correct for any deviation of the measurement point from the reference distance from the source	-	0.10
$k_{back,ch}$	Factor for the lack of backscatter in the chamber phantom	-	0.05
$k_{unif,ch}$	Factor to correct for the radial non-uniformity of the beam	0.05	-
R	Repeatability	0.15	-
$u_c(N_{D,g})$	Combined standard uncertainty	0.49	

7.4 UNCERTAINTIES IN THE MEASUREMENT OF DOSE TO WATER USING THE TRANSFER STANDARDS

Table 12 Uncertainties in the measurement of dose to water using the transfer standards

Symbol	Quantity, source of uncertainty	Type A	Type B
$N_{D,g}$	Transfer standard dose to graphite sensitivity	-	0.49
$\frac{s_{w/air}}{s_{g/air}}$	Stopping power ratio (conversion from graphite to water)	-	0.30
p_w/p_g	Perturbation ratio	-	0.30
R_{trans}	Repeatability of transfer standard dose per MU	0.22	-
$k_{elec,std}$	Electrometer charge calibration (nC/'nC')	-	0.06
$k_{elec,mon}$	Electrometer charge calibration (nC/'nC')	-	0.06
k_{ion}	Ion recombination correction	0.05	-
k_{pol}	Polarity effect correction	0.05	-
$I_{leakage,std}$	Leakage current (A)	0.05	-
$I_{leakage,mon}$	Leakage current (A)	0.05	-
P	Pressure (kPa)	0.02	-
T_{std}	Temperature (K)	0.01	-
T_{mon}	Temperature (K)	0.01	-
k_{depth}	Factor to correct for the deviation of the depth of measurement of the chamber in the water phantom from the reference position	-	0.10
k_{dist}	Factor to correct for any deviation of the measurement point from the reference distance from the source	-	0.10
$u_c(D_w/MU)$	Combined standard uncertainty	0.71	

7.5 UNCERTAINTIES IN THE CALIBRATION OF A SECONDARY STANDARD

Table 13 Uncertainties in the calibration of a secondary standard

Symbol	Quantity, source of uncertainty	Type A	Type B
D_w/MU	Dose to water/MU	-	0.71
$k_{elec,std}$	Electrometer charge calibration (nC/'nC')	-	0.06
$k_{elec,mon}$	Electrometer charge calibration (nC/'nC')	-	0.06
k_{ion}	Ion recombination correction	0.05	-
k_{pol}	Polarity effect correction	0.05	-
$I_{leakage,std}$	Leakage current (A)	0.05	-
$I_{leakage,mon}$	Leakage current (A)	0.05	-
P	Pressure (kPa)	0.02	-
T_{std}	Temperature (K)	0.01	-
T_{mon}	Temperature (K)	0.01	-
k_{depth}	Factor to correct for the deviation of the depth of measurement of the chamber in the water phantom from the reference position	-	0.10
k_{dist}	Factor to correct for any deviation of the measurement point from the reference distance from the source	-	0.10
R	Repeatability	0.10	-
$u_c(N_{D,w})$	Combined standard uncertainty	0.75	

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