COMPARISON OF THE NPL WATER CALORIMETER WITH OTHER DOSIMETRIC TECHNIQUES FOR HIGH ENERGY PHOTON BEAMS.

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ABSTRACT

At present, the primary standard of absorbed dose to water at NPL in high energy photon beams is a graphite calorimeter. However the quantity of interest in radiation dosimetry is absorbed dose to water. Therefore, a new absorbed dose to water standard based on water calorimetry is being developed at NPL. The calorimeter operates at 4 °C, with temperature control being provided by a combination of liquid and air cooling. The sealed glass inner vessel of the calorimeter has been designed to minimise the effect of non-water materials on the measurement of absorbed dose. Measurements of absorbed dose to water made in 6, 10 and 19 MV photon beams agreed within the measurement uncertainties with those determined using the primary standard graphite calorimeter. Also the absorbed dose to water measured using the water calorimeter agrees with that based on the air kerma standards for ^{60}Co γ-radiation within the uncertainties. The development of the water calorimeter will lead to a very robust dosimetry system at NPL, where the absorbed dose to water can be determined using three independent techniques.

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1. INTRODUCTION.

The quantity absorbed dose is used to specify the amount of energy deposited in a material by ionising radiation. It is defined as the energy absorbed per unit mass and is assigned the SI unit, gray (Gy) where 1 Gy is equivalent to 1 Jkg^{-1}. The absorbed dose depends on both the radiation field and the material with which the radiation interacts. Knowledge of the absorbed dose is required for a range of applications involving ionising radiation, but the most demanding in terms of accuracy is that for radiotherapy. The goal of radiotherapy treatment planning is to predict accurately the absorbed dose received by all irradiated tissue. In general, the required uncertainty on the dose is in the range from 5%[1] to 3%[2]. As a first step to determine the absorbed dose to tissue, the absorbed dose to water is determined for a well defined reference geometry. Water is chosen because its radiation absorption characteristics are similar to those of tissue.

The only direct method of determining absorbed dose to water is using a water calorimeter. However, primary standards of absorbed dose to water are not yet widely available, so at NPL absorbed dose to water is realized via a graphite calorimeter. Prior to graphite calorimetry the only method at NPL of determining absorbed dose to water for high energy photon beams was based on an air kerma calibration using 2 MV X-rays [3].

Therefore, in 1995 NPL initiated a research project to build a water calorimeter that would test the validity of the existing procedure. The construction and operating procedure for the new water calorimeter is described in a separate report [4].

The implementation and validation of a water calorimeter will lead to a very robust dosimetry system at NPL where the absorbed dose to water for high energy X-rays can be determined using three independent methods, namely water calorimetry, graphite calorimetry and that based on an air kerma standard at ^{60}Co, each method having its own unique correction factors and dosimetry problems. (Recently at NPL the 2MV Van der Graff generator has been replaced with a Mobaltron ^{60}Co γ-radiation source).

In this report the absorbed dose to water measured using the NPL prototype water calorimeter is compared with that determined using the NPL graphite calorimeter and that based on an air kerma measurement using ^{60}Co γ-rays.

2. COMPARISON OF ABSORBED DOSE TO WATER MEASURED WITH THE WATER CALORIMETER TO THAT USING THE PRIMARY STANDARD GRAPHITE CALORIMETER.

2.1 BRIEF DESCRIPTION OF ABSORBED DOSE TO WATER DETERMINED USING THE PRIMARY STANDARD GRAPHITE CALORIMETER.

In 1988 NPL launched a calibration service [10] for secondary standard dosemeters in terms of absorbed dose to water for ^{60}Co gamma radiation and seven X-ray qualities between 4 and 19 MV.

The NPL primary standard [6] is a graphite calorimeter following the design of Domen [7]. Absorbed dose to graphite is measured in a 2 cm diameter, 2.75 mm thick graphite disc that forms the core of the calorimeter. The main corrections to the calorimeter measurements are for the effects of the gaps around the core [8] and the energy losses during the electrical calibration.

Three working standard NE2561/NE2611 ionisation chambers are compared directly with the calorimeter in a graphite phantom. Their calibration factors in terms of absorbed dose to graphite are converted to absorbed dose to water following the work of Burns [9], who used cavity theory and the photon fluence scaling theorem to derive a calibration factor in terms of absorbed dose to water. In the final stage of the procedure, secondary standard ionisation chambers are compared directly with the working standards in a water phantom. The uncertainty on the absorbed dose to water calibration factor for the secondary standard chambers is 1.4% (95% confidence limit) [10].

This is a complex procedure and a direct method to determine absorbed dose to water would be preferable.

2.2 WATER CALORIMETRY

The water calorimeter that was designed and built at NPL is described in detail by Williams and Rosser [4] so only a brief description will be given here. Figure 1 shows the calorimeter vessel which contains high purity water that has been saturated with hydrogen. This should result in the water having zero heat defect after an initial dose of approximately 30 Gy [5]. The temperature rise due to the incident radiation (typically 0.2 mK for a dose of 1 Gy) is measured using two small thermistor beads 0.3 mm in diameter. The vessel is held in a 25 x 25 cm phantom that is maintained at 4 °C to minimize convection.

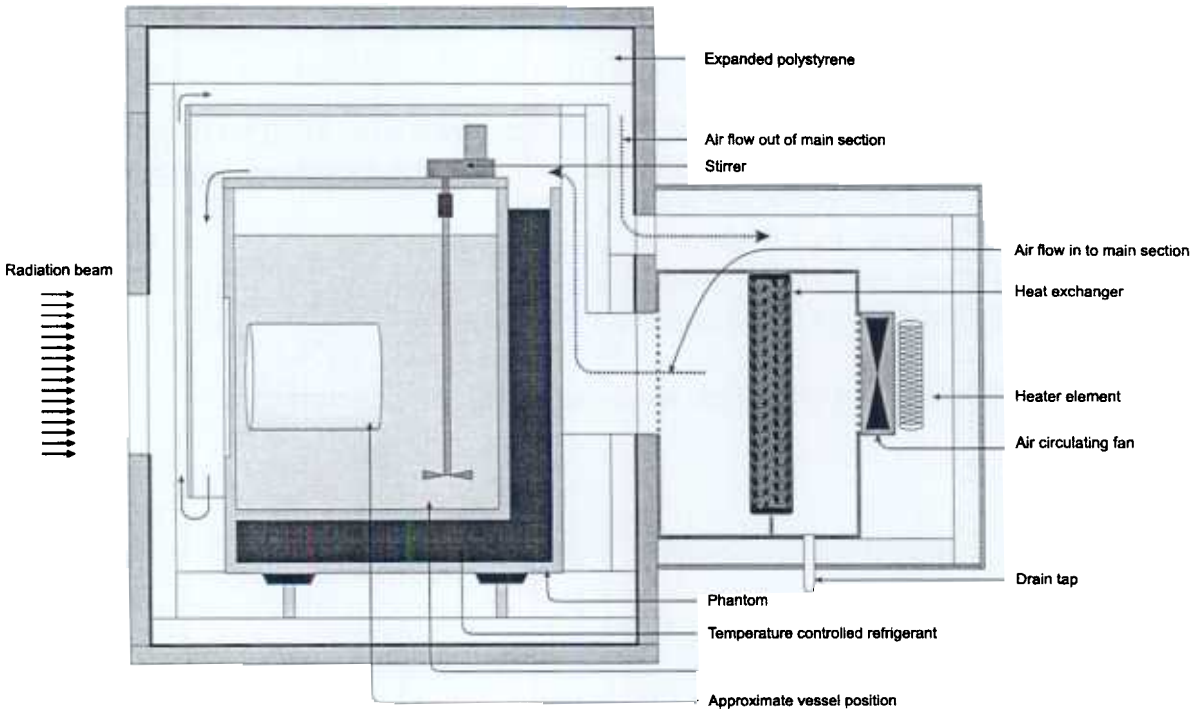


Figure 1 Schematic diagram of the NPL design of water calorimeter.

For the measurements described in this report, the temperature rise due to the radiation was measured by connecting each of the thermistor probes to its own DC Wheatstone bridge. The bridges are powered by a 0.4 - 2 V, NPL designed and built, battery powered precision voltage supply. The bridge output voltages are read by two digital multi-meters, each with a resolution of 10 nV. The out-of-balance bridge voltages are calibrated against a platinum resistance thermometer. The end result is a system with a maximum temperature resolution of 0.5 μK, and a RMS noise of 3 μK.

To compare the water and the graphite calorimeters three NE2561/NE2611 ionisation chambers were used as transfer chambers. This does not significantly increase the

uncertainties in the comparison. The three chambers have previously been calibrated in terms of absorbed dose to water using the graphite calorimeter. They were calibrated using the water calorimeter by placing them individually at 5 or 7 cm depth (depending on the energy) in a 30 x 30 cm water phantom next to the water calorimeter. The response of the chambers was measured at the beginning and end of each set of calorimeter measurements.

2.3 RESULTS OF THE COMPARISON.

Figure 2a, 2b and 2c shows a comparison of the absorbed dose to water determined using the water calorimeter to that using the graphite calorimeter. The water calorimetry does not include a correction for the conversion of the absorbed dose to water in the calorimeter vessel to that in a 30 x 30 cm phantom, although this is likely to be small (approximately 0.1%).

The three measurements using the water calorimeter for X-rays at a TPR of 0.779 (X-rays generated at 16 MV) were carried out under different measurement conditions.

1. Bridge voltage set to 1 V, dose-rate approximately 2.8 Gy/min.
2. Bridge voltage set to 0.4 V, dose-rate approximately 2.8 Gy/min.
3. Bridge voltage set to 1 V, dose-rate approximately 1.4 Gy/min.

For a discussion of the uncertainties, see Section 4.

Figure 2a Comparison of the absorbed dose to water measured using the NPL water calorimeter to that using the NPL primary standard photon graphite calorimeter for a NE2611 chamber, Serial Number 122.

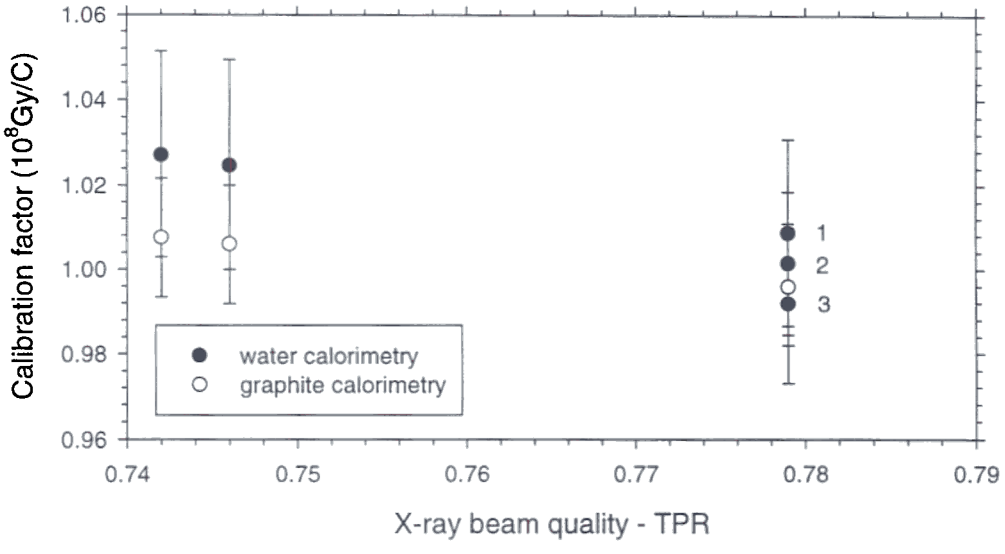


Figure 2b Comparison of the absorbed dose to water measured using the NPL water calorimeter to that using the NPL primary standard photon graphite calorimeter for a NE2611 chamber, Serial Number 131.

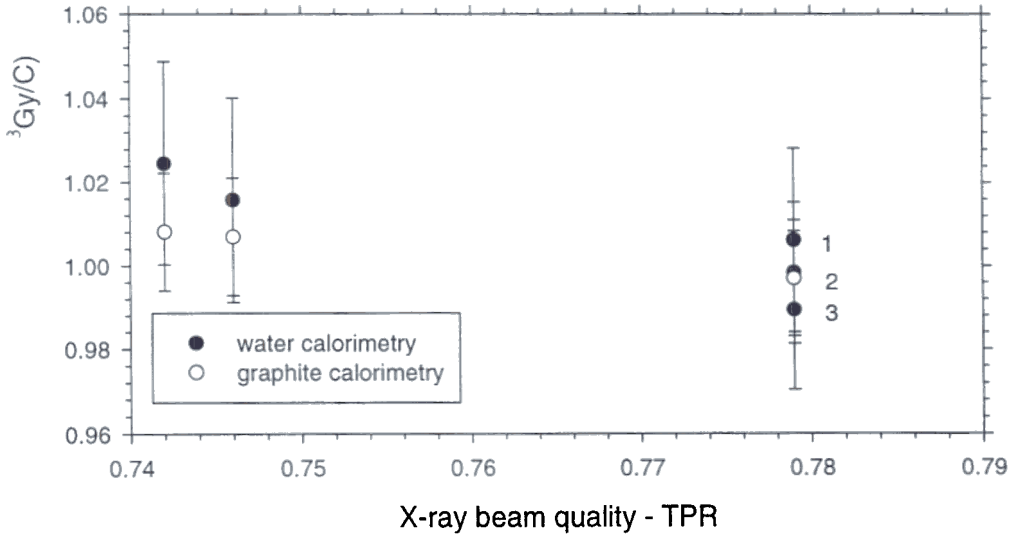


Figure 2c Comparison of the absorbed dose to water measured using the NPL water calorimeter to that using the NPL primary standard photon graphite calorimeter for a NE2561 chamber, Serial Number 295

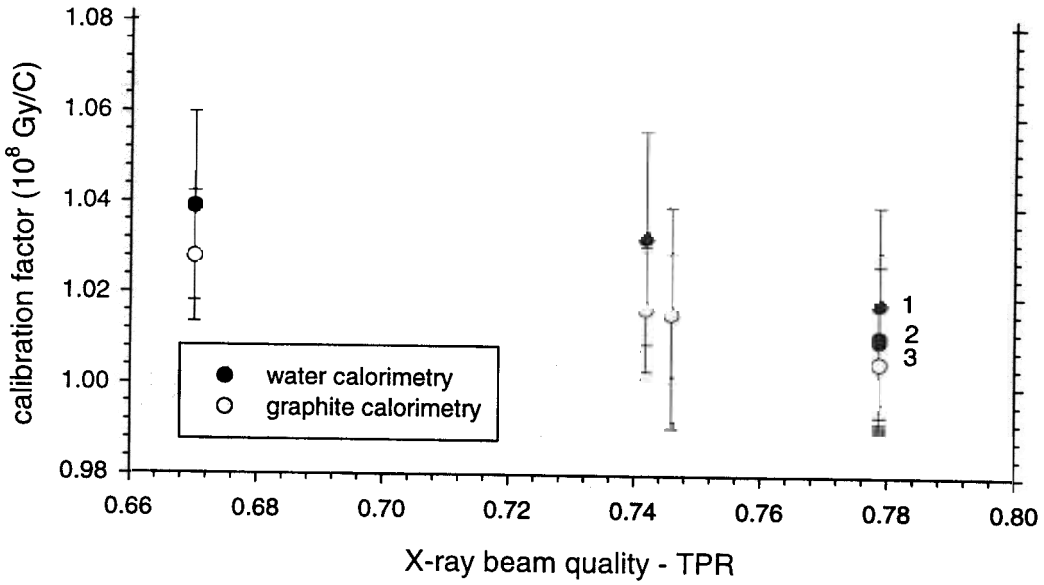


TABLE 1 Comparison of the absorbed dose to water determined using the water calorimeter to that using the graphite calorimeter.

TPR	Ratio of calibration factors determined using the water calorimeter to that using the graphite calorimeter.		
	NE2611 s/n 122	NE2611 s/n 131	NE2561 s/n 295
0.670			1.011
0.742	1.019	1.016	1.016
0.746	1.019	1.009	1.000
0.779 (0.4 V bridge voltage)	1.013	1.009	1.013
0.779 (1 V bridge voltage)	1.006	1.001	1.005
0.779 (half the dose-rate)	0.996	0.992	1.006

2.4 DISCUSSION

Table 1 shows that the calibration factors determined using the water calorimeter to that determined using the graphite calorimeter are similar for all of the chambers.The calibration factors determined using the graphite and water calorimeters agree within experimental uncertainty (see Table 3).

3. COMPARISON OF THE ABSORBED DOSE TO WATER DETERMINED USING THE WATER CALORIMETER TO THAT DETERMINED USING A CHAMBER CALIBRATED IN TERMS OF AIR KERMA USING ^{60}Co γ-RAYS

There are several different protocols for determining the absorbed dose to water based on a chamber that has been calibrated in air in terms of air kerma using ^{60}Co γ- rays. It is therefore worthwhile to compare the absorbed dose to water in a phantom irradiated by high energy photons using the procedure and reference data for the physical quantities given in four of the protocols, namely HPA [3], NCS [11], AAPM [12] and IAEA [13]. The comparsion of the Codes of Practice is given in Appendix A. The comparison shows that the codes differ in the determination of absorbed dose to water by ±2%. Therefore, for this comparison, the factors used to convert from air kerma to absorbed dose to water were mean values taken from the HPA, AAPM, NCS and IAEA Codes of Practice

3.1 COMPARISON OF THE ABSORBED DOSE TO WATER MEASURED USING THE WATER CALORIMETER TO THAT BASED ON AN AIR KERMA MEASUREMENT AT ^{60}Co.

Figures 3a and 3b show the comparison of the absorbed dose to water measured using the water calorimeter to that based on an air kerma measurement at ^{60}Co.

The three measurements using the water calorimeter for X-rays at a TPR of 0.779 (X-rays generated at 16 MV) were carried out under different measurement conditions.

1. Bridge voltage set to 1 V, dose-rate approximately 2.8 Gy/min.
2. Bridge voltage set to 0.4 V, dose-rate approximately 2.8 Gy/min.
3. Bridge voltage set to 1 V, dose-rate approximately 1.4 Gy/min.

Figure 3a: Comparison of the calibration factor for a NE2611, Serial Number 122 chamber based on the mean of the four Codes of Practice to that determined using the water calorimeter.

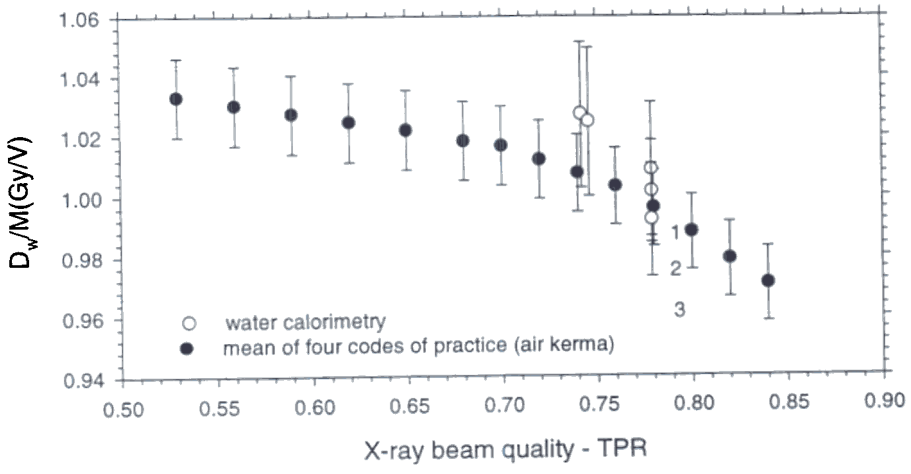
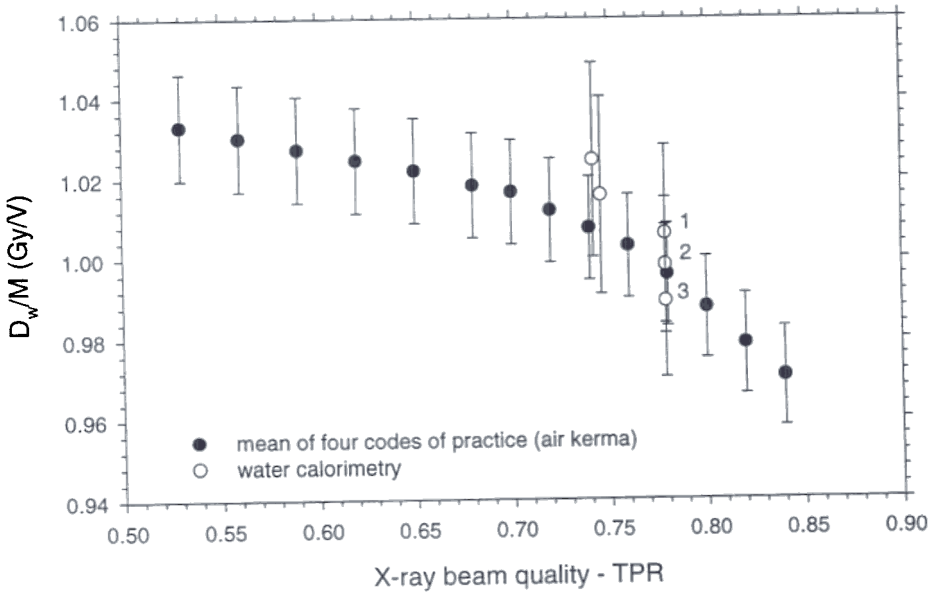


Figure 3b: Comparison of the calibration factor for a NE2611, Serial Number 131 chamber based on the mean of the four Codes of Practice to that determined using the water calorimeter.



4. UNCERTAINTIES.

The uncertainties (quoted as standard uncertainties according to NAMAS [19]) in the determination of absorbed dose are given in Tables 2 and 3. The reported expanded uncertainties are based on the standard uncertainies multiplied by a coverage factor k=2, providing a level of confidence of approximately 95%.

TABLE 2: UNCERTAINTIES ASSOCIATED WITH THE CALIBRATION FACTOR FOR A NE2561/NE2611 IONISATION CHAMBER DETERMINED BY DIRECT COMPARISON WITH THE WATER CALORIMETER.

Source of uncertainty	**Standard uncertainty (±) (%)**	
	Type A	**Type B**
Chamber Measurements		
charge calibration of the electrometer		0.1
calibrated in a phantom instead of the calorimeter vessel		0.1
Water calorimeter		
calibration of the PRT		0.05
calibration of the thermistors.	0.06	
correction for heat conduction in the calorimeter		0.1
specific heat capacity of water.		0.6
Zero heat defect	0.5	
Quadrature sum	0.50	0.63

TABLE 3: COMBINED UNCERTAINTIES ASSOCIATED WITH THE CALIBRATION FACTOR FOR A NE2561/NE2611 IONISATION CHAMBER DETERMINED BY DIRECT COMPARISON WITH THE WATER CALORIMETER.

	Source of uncertainty	Standard uncertainty (±) (%)					
TPR		0.670	0.742	0.746	0.779*	0.779	0.779‡
Type A	**Chamber measurements**						
	Reproducibility of the ionisation current at the begining and end of a set of calorimeter measurements	0.2	0.2	0.2	0.2	0.4	0.4
	Calorimeter measurments						
	Calorimeter reading	0.47 (n=13)	0.62 (n=25)	0.65 (n=12)	0.22 (n=11)	0.47 (n=12)	0.36 (n=15)
	Combined uncertainty with Table 1	0.72	0.82	0.84	0.58	0.79	0.74
Type B	Depth in water	0.55	0.44	0.44	0.45	0.45	0.45
	Combined uncertainty with Table 1	0.84	0.77	0.77	0.77	0.77	0.77
Combined total uncertainty		1.11	1.13	1.14	0.96	1.10	1.07
95% confidence limit (k=2)		2.22	2.26	2.28	1.92	2.20	2.14

* Bridge voltage set to 1 V, dose-rate approximately 2.8 Gy/min
+Bridge voltage set to 0.4 V, dose-rate approximately 2.8 Gy/min
‡Bridge voltage set to 1 V, dose-rate approximately 1.4 Gy/min

TABLE 4: COMBINED UNCERTAINTIES ASSOCIATED WITH THE MEASUREMENT OF ABSORBED DOSE TO WATER USING A NE2561/NE2611 IONISATION CHAMBER, BASED ON A CHAMBER CALIBRATED IN TERMS OF AIR KERMA.

Source of uncertainty	Standard uncertainty (±) (%)
Interaction coefficients	0.4
Calibration factor in terms of air kerma	0.5
Combined uncertainty	0.64
95% confidence limit (k=2)	1.28

Only the IAEA Code of Practice details the uncertainty associated when using the Code, therefore the uncertainty associated with the interaction coefficients was taken from this Code. The uncertainty associated with the air kerma calibration factor was taken from an NPL calibration certificate.

4.1 DERIVATION OF UNCERTAINTIES ASSOCIATED WITH THE ABSORBED DOSE DETERMINED USING THE WATER CALORIMETER.

The uncertainties in this report have been estimated following UKAS recommendations [19]. Details of specific uncertainties are given below:

1) Specific heat capacity of water: The range of values were taken from Touloukian et al [20], and the overall uncertainty was estimated by assuming a rectangular probability distribution.

2) Reproducibility of the ionisation current at the beginning and end of a set of calorimeter measurements: The overall uncertainty was estimated by assuming a rectangular probability distribution.

3) Zero heat defect: It was assumed that if a zero heat defect had been attained then there would be no change in the response of the calorimeter with accumulated dose. The response of the calorimeter could only be obtained within the random uncertainty of the calorimeter measurements, therefore the uncertainty in attaining a zero heat defect was taken as the mean random uncertainty for all of the calorimeter measurements. It must be realized that this incorporates many uncertainties including the electrical noise but due to our lack of knowledge at the present time this is our best estimate of zero heat defect.

4) Depth in water: It is estimated that the accuracy in the depth in water is ± 1mm. This was converted to an estimate of the accuracy in the absorbed dose to water using BJR Supplement 25 [21].

5. DISCUSSION

It can be seen from Figures 3a and 3b that the absorbed dose to water measured using the water calorimeter agrees with that based on the air kerma standards for ^{60}Co γ-radiation within the uncertainties. There does not at this stage appear to be a preferential method of determining absorbed dose to water as all three techniques have large uncertainties. However the water calorimeter has one main advantage as it attempts to measure absorbed dose to water directly.

The aim of the water calorimetry project at NPL in the future will be to reduce the uncertainties associated with the specific heat capacity of water, heat defect and to improve the measurement system.

6. ACKNOWLEDGEMENTS.

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APPENDIX A. COMPARISON OF THE ABSORBED DOSE TO WATER DETERMINED USING THE WATER CALORIMETER TO THAT DETERMINED USING A CHAMBER CALIBRATED IN TERMS OF AIR KERMA USING ^{60}Co γ-RAYS

A.1 PROTOCOL FORMALISM.

The equations relating the ionisation reading, M, to absorbed dose to water D_W (in grays) at the radiation quality of users (u or λ) photon beams are given below. The nomenclature has been altered slightly to give a consistent set of equations. The equations have also been adjusted so that they convert from air kerma to absorbed dose to water and not the old unit of exposure (Röntgen).

A. 1. 1 HPA (Hospital Physics Association) [3]

In the UK, the HPA Code [3] has been superseded by the IPSM Code [14] that is based on a chamber calibrated directly in terms of absorbed dose to water (see Section 2.1). In the HPA Code the absorbed dose to water (D_w) is given by:

$$D_w = 1.139 \cdot M_u \cdot N_k \quad C_\lambda \qquad (1)$$

where

1.139 converts the calibration factor from exposure in R to air kerma in Gy,

M_u is the instrument reading, corrected for any differences between ambient air conditions at the time of measurement and the standard conditions for which the calibration factor applies,

N_k is the calibration factor, given by the national standard laboratory, which converts the instrument reading of the chamber plus build-up cap irradiated in air to air kerma in Gy for 2MV X-rays or ^{60}Co γ-rays for standard ambient conditions,

C_λ is a conversion factor that depends on the quality of the user's beam and on the ion chamber used.

A.1.2. NCS (Nederlandse Commissie voor Stralingsdosimetrie) [11]

In this Code of Practice, the absorbed dose to water can be derived from a similar expression to that given in the HPA Code, namely:

$$D_{w,u} = M_. \quad N_k \cdot C_{w,u} \qquad (2)$$

In the appendices of the Code, equation (2) is explained in more detail.

$$C_{w,u} = (1-g) \cdot \Pi k_i \quad s_{wall,air} \quad \Pi p_i \qquad (3)$$

where

$s_{wall,air}$ is the wall to air mass stopping power ratio.

g is the fraction of energy of secondary charged particles that is lost to bremsstrahlung.

Πk_i is the product of the calibration factors to be applied to the ^{60}Co calibration factor in air, and is given by

$$\Pi k_i = k_{att} \quad k_m \cdot k_{st} \cdot k_{ce} \qquad (4)$$

where

k_{att} is a correction for attenuation (absorption and scattering) in the wall and build-up cap of the ionisation chamber.

k_{st} is a correction for the stem effect for the field size employed.

k_{ce} is a correction for the effect of the central electrode on the response of the chamber during calibration.

k_m is a correction for the difference in composition between the wall plus build-up cap (ca) and air, and is given by

$$k_m = \left[\quad s_{wall,air} \quad \left(\frac{\mu_{en}}{\rho} \right)_{air,wall} + (1 - \alpha)\, s_{ca,air} \left(\frac{\mu_{en}}{\rho} \right)_{air,ca} \right]^{-1} \qquad (5)$$

where

α is the fraction of the ionisation due to electrons set in motion in the chamber wall.

$(1-\alpha)$ is the fraction of ionisation arising in the build-up cap,

$(\bar{\mu}_{en}/\rho)_{air,wall}$ and $(\bar{\mu}_{en}/\rho)_{air,ca}$ are the air/wall and air/build-up cap mass energy absorption coefficients respectively,

$s_{ca,air}$ is the build-up cap to air mass stopping power ratio.

When the chamber is used in the phantom the product of the correction factors Πp_i to be applied to the measurement is given by:

$$\Pi p_i = p_{wall} \cdot p_d \quad p_{ce} \tag{6}$$

p_d is the displacement correction factor that corrects for the displacement of the effective centre of the ionisation chamber,

p_{ce} corrects for the effect of the central electrode on the response of the chamber during the measurements in the water phantom,

p_{wall} corrects for the differences in composition between the ionisation chamber wall and water, where p_{wall} is given by

$$p_{wall} = \alpha \quad s_{wall,w} \left(\frac{\overline{\mu}_{en}}{\rho} \right)_{w,wall} + (1-\alpha) \tag{7}$$

where

$\left(\frac{\overline{\mu}}{\rho} \right)_{w,wall}$ is the ratio of mass energy absorption coefficients for water to the wall material,

$s_{wall,w}$ is the ratio of stopping powers for the wall material to water.

A.1.3 AAPM (American Association of Physicists in Medicine) [12]

In the AAPM protocol the absorbed dose to water is given by:

$$D_{water} = M \quad N_{gas} \left(\frac{\overline{L}}{\rho} \right)_{air}^{wall} \quad P_{ion} \quad P_{repl} \quad P_{wall} \tag{9}$$

where

$\left(\frac{\overline{L}}{\rho} \right)_{wall}^{air}$ is the mean restricted collision mass stopping power of the phantom material to that of the chamber gas (air) (Δ set to 10 keV).

P_{ion} ion recombination correction factor applicable to the calibration of the user's beam.

P_{repl} is a factor that corrects for the replacement of phantom material by an

ionisation chamber.

P_{wall} is unity when the chamber wall and dosimetry phantom are of the same composition.

The cavity-gas calibration factor N_{gas} is the dose to the air in the chamber per unit electrometer reading. It is a constant for a chamber for all radiation qualities for which the value of (W/e) is the same as that for ^{60}Co. N_{gas} is given by:

$$N_{gas} = N_x \frac{2.58 \times 10^{-4} \quad (W/e) \cdot A_{ion} \cdot A_{wall} \quad \beta_{wall}}{\alpha \quad (\bar{L}/\rho)_{gas}^{wall} \quad (\overline{\mu_{en}}/\rho)_{wall}^{air} + (1-\alpha) \cdot (\bar{L}/\rho)_{gas}^{ca} \cdot (\overline{\mu_{en}}/\rho)_{ca}^{air}} \qquad \textbf{(11)}$$

where

N_x is the calibration factor in terms of exposure,

A_{ion} ion-collection efficiency in the user's chamber at the time of ^{60}Co exposure calibration,

A_{wall} correction for attenuation and scatter in the wall and build-up cap of the user's chamber when exposed in air to ^{60}Co gamma rays,

β_{wall} is the quotient of absorbed dose by the collision fraction of kerma in the chamber wall.

$\left(\frac{\overline{\mu}}{\rho}\right)_{wall}^{air}$ is the ratio of mass energy absorption coefficients of air to the wall material,

$\left(\frac{\overline{\mu}}{\rho}\right)_{ca}^{air}$ is the ratio of mass energy absorption coefficients of air to the build-up cap,

$\left(\frac{\overline{L}}{\rho}\right)_{gas}^{wall}$ is the mean restricted collision mass stopping power of the wall material to that of the chamber gas (air).

$\left(\frac{\overline{L}}{\rho}\right)_{ca}^{wall}$ is the mean restricted collision mass stopping power of the chamber gas (air) to that of the build-up cap.

α is the fraction of ionization due to electrons from the chamber wall, and

$(1-\alpha)$ is the fraction of ionisation arising in the build-up cap,

A.1.4 IAEA (International Atomic Energy Agency) [13]

The absorbed dose to water at the effective point of measurement (D_w) is given by:

$$D_w = M_{,} \quad N_{D,C} \cdot (s_{w,air})_u \quad P_u \tag{16}$$

where:

$_{D,C}$ is the absorbed dose calibration factor at ^{60}Co,

$$N_{D,C} = N_k \quad (1-g) \quad k_{att} \quad k_m \tag{17}$$

P_u allows for the non-water equivalence of an ionisation chamber.

k_{att} allows for attenuation in the walls of an ionisation chamber irradiated for calibration purposes.

k_m accounts for the non air equivalence (at the calibration quality) of the ionisation chamber wall and build-up cap materials, and is given by

$$k_m = \alpha \quad s_{air,wall} \quad \left(\frac{\mu_{en}}{\rho}\right)_{wall,air} + (1 - \alpha)\, s_{air,ca} \left(\frac{\mu_{en}}{\rho}\right)_{ca,air} \tag{18}$$

where

$s_{air,wall}$ is the air to chamber wall mass stopping power ratio.

$s_{air,ca}$ is the air to build-up cap mass stopping power ratio.

$\left(\frac{\overline{\mu}}{\rho}\right)_{wall,air}$ is the ratio of mass energy absorption coefficients of wall material to the air,

$\left(\frac{\overline{\mu}}{\rho}\right)_{ca,air}$ is the ratio of mass energy absorption coefficients of build-up cap to air,

Appendix A2 PROTOCOL DISCUSSION.

The four protocols discussed in this report vary in their complexity from the simple HPA Code where C_λ factors are given for one chamber, to the more complex AAPM Code that covers many different types of chambers.

Figure A2.1 Comparison of the HPA, AAPM, IAEA and NCS Codes of Practice for a NE2561/NE2611 chamber.

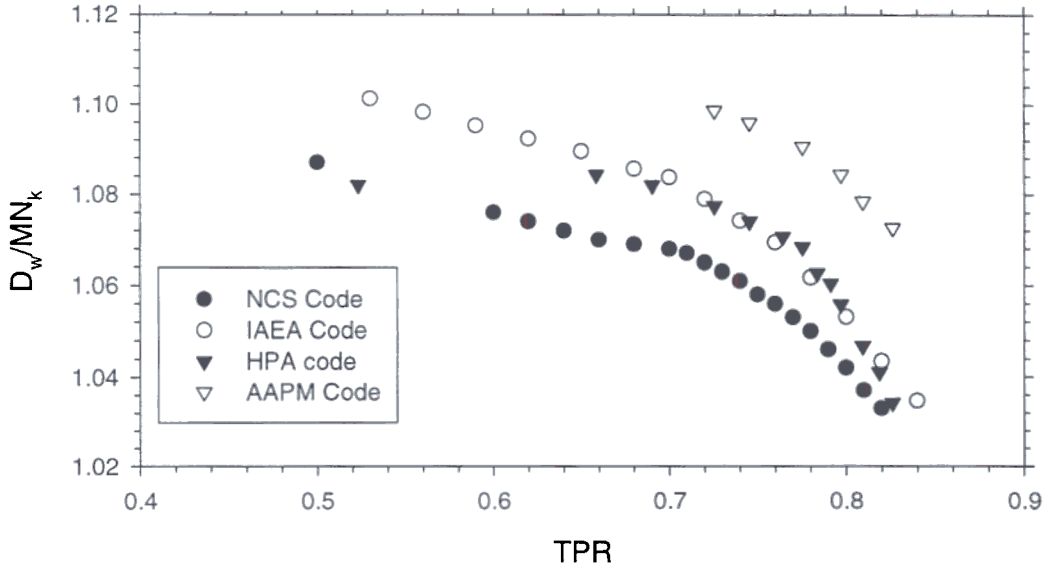
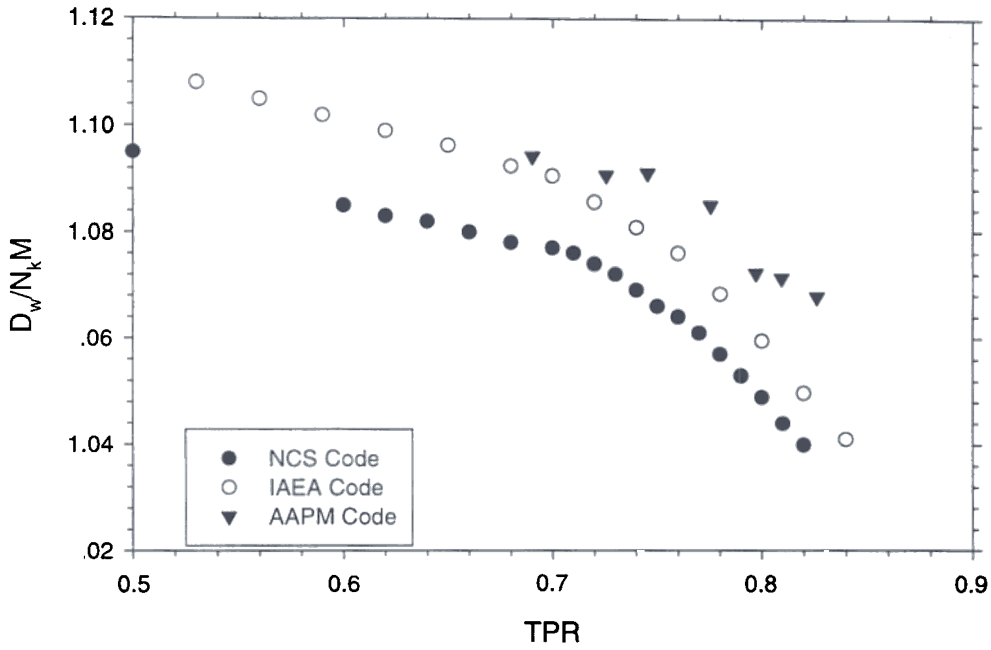


Figure A2.1 show that for NE2561/NE2611 chambers, the four codes differ in the determination of absorbed dose to water within ±2%. Figure A2.2 shows that the data given in the AAPM protocol for the NE2571 is closer to the other Codes than for the NE2561. The four codes differ in many respects as discussed below.

Figure A2.2 Comparison of the AAPM, IAEA and NCS Codes for a Farmer type NE2571 chamber.



A2.1 Ionisation chambers

Table 1 outlines the differences in the types of chambers that can be used in the Codes ranging from the IAEA that give values of the product $k_m k_{att}$ for 37 different chambers to the HPA Code which is limited to one chamber (NE2561/NE2611 secondary standard).

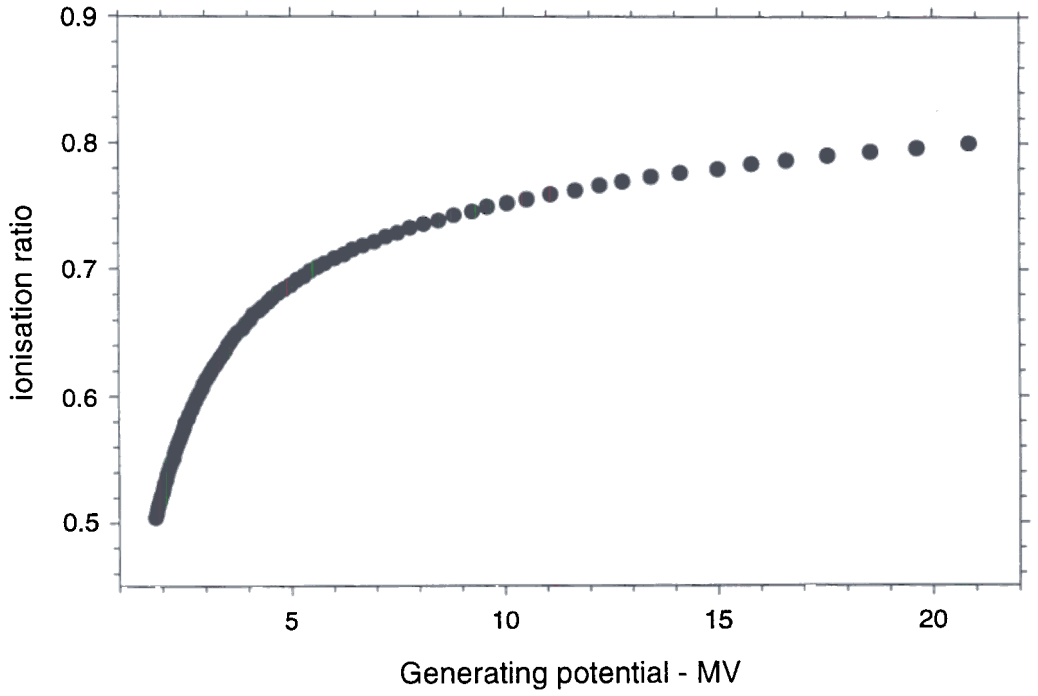
Table A2.1 Chambers recommended in the Codes of Practice.

Code	Shape	Chamber dimensions	Factors quoted in the code.
AAPM	cylindrical	internal diameter should not be greater than 1 cm and its internal height should be such that the radiation fluence is uniform from end to end	A_{wall} for 12 commercially available chambers, $(L/\rho)_{wall,air}$ and $(\bar{\mu}_{en}/\rho)_{air,wall}$ for 8 materials
HPA	cylindrical	limited to one commercially available chamber NE2561	
IAEA	cylindrical	wall < 0.1 $g.cm^{-2}$ collecting electrode≤2 mm Internal cavity diameter≤7 mm Internal cavity length < 25mm	k_m for 9 materials, $k_m.k_{att}$ for 37 commercially available chambers. $S_{wall,air}$ for 7 materials
NCS	cylindrical	only graphite wall recommended	$C_{w,u}$ for 3 commercially available chambers.

A2.2 Quality index

Specification of the beam quality is vitally important because energy dependent factors such as the stopping power ratio, perturbation corrections, etc., are required to calculate absorbed dose to water. However, there is no universally accepted method of defining the quality of the beam. The AAPM recommends that the beam quality index is the ratio of ionisation measurements for a fixed source-detector distance at depths 10 and 20 cm but give some data in terms of generating potential MV. The NCS is more specific in that it requires a 10 x 10 cm field at the geometric centre of the chamber. The IAEA Code recommends the ratio of absorbed doses at 10 and 20 cm depth for a constant source- detector distance and 10 x 10 cm field at the plane of the chamber. In practice, the AAPM, IAEA and NCS beam quality indices are the same, as the IAEA Code gives no data to convert the ionisation at 10 and 20 cm depth to absorbed dose. The main difficulty is that the HPA Code quotes the quality of the beam in MV. For this comparison Figure A2.3 (taken form the AAPM code) was used to convert from MV to ionisation ratio.

Figure A2.3: Relationship between ionisation ratio and MV taken from the AAPM code.



A2.3 Effective point of measurement

In the process of determining absorbed dose to water an ionisation chamber is inserted into a water phantom. Various phenomena occur which cause the electron fluence in the cavity to differ from the fluence in the water in the absence of the chamber. There are two major effects which are called the perturbation correction in this report. Firstly, a correction for the non-water equivalence of the chamber materials including the wall, central electrode and sleeve. The second effect corrects for the chamber measuring an average dose on the slope of the depth dose curve. The second effect can be taken into account by placing the centre of the chamber at the measurement point and applying a correction or placing the centre of the chamber at a point upstream from the measurement point. The IAEA Code recommends that the dose is measured at the effective point of measurement (i.e. 0.6r for high energy photons and 0.5r for ^{60}Co, where r is the radius of the effective volume of the chamber) in front of the chamber. The AAPM, HPA and NCS Codes do not correct for this effect and state that the reference point is at the centre of the chamber. For this comparison of D_W/N_K, the centre

of the chamber is taken as the reference point. For the IAEA Code it is assumed that the variation of D_w and M with depth are similar and therefore no correction is applied.

Central electrode.

A correction is required to take into account the non-air equivalence of the central electrode. For higher photon energies the correction due to the aluminum electrode decreases as the photon energy increases and the correction to k_m (at ^{60}Co) and P_u will partly cancel. The IAEA and NCS Codes assume that this correction is close to unity whereas the HPA and AAPM codes do not mention it.

The energy required to produce an ion pair in air (W/e) and the fraction of energy of secondary charged particles that is lost to bremsstrahlung (g).

Over the years the value of the energy required to produce an ion pair in air (W/e) has changed. This is required to convert from exposure to air kerma; it is used at national standards laboratories where the primary standards measure exposure. The AAPM protocol adopts a value of 33.7 JC^{-1}, whereas the IAEA and NCS protocols adopt the latest value recommended by CCEMRI [15]; that is 33.97 JC^{-1} . In between this is the HPA protocol that adopts a value of 33.85 JC^{-1}.

Similarly the value of *g* has been revised over the years. The HPA and AAPM protocols quote a value of 0.005 whereas the IAEA and NSC protocols quote 0.003.

A2.6 Stopping power ratio.

Figure A2.1 shows that there are significant differences between the four Codes used in this paper. One reason for these differences is the values of the mass stopping power ratio of water to air (see Table A2.2). This may be due to either the monoenergetic values or the method of averaging them over the spectra at the point of measurement. Figure 6 shows that the AAPM values are greater than those used in the IAEA and NCS Codes by approximately 1%.

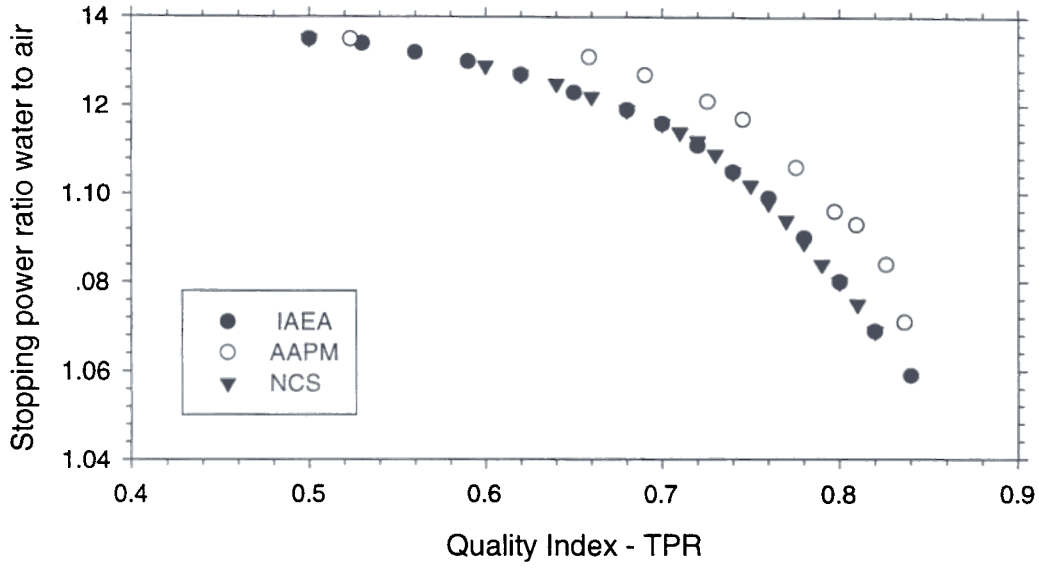


Figure A2.4 Comparison of the stopping power ratio of water to air given in the AAPM, IAEA and NCS Codes of Practice.

TABLE A2.2 COMPARISON OF STOPPING POWER RATIO OF WATER TO AIR.

Code	Stopping power ratios	Restricted	Comments
AAPM	Cunningham and Schultz [16]	restricted (Δ=10 keV)	
HPA	Berger and Seltzer [17]	unrestricted	averaged over the continuous secondary electron energy spectrum generated at each quality.
IAEA	Berger and Seltzer [17]	restricted	Monte Carlo calculations by Andreo and Brahme [18] were used to generate electron energy spectra and to determine the average stopping power values.
NCS	Berger and Seltzer [17]	restricted	Monte Carlo calculations by Andreo and Brahme [18] were used to generate electron energy spectra and to determine the average stopping power values.