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Original Research Article

An on-site dosimetry audit for high-energy electron beams

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ABSTRACT

Background and purpose: External dosimetry audits are powerful quality assurance instruments for radiotherapy. The aim of this study was to implement an electron dosimetry audit based on a contemporary code of practice within the requirements for calibration laboratories performing proficiency tests. This involved the determination of suitable acceptance criteria based on thorough uncertainty analyses.

Materials and methods: Subject of the audit was the determination of absorbed dose to water, D_w, and the beam quality specifier, $R_{50,dos}$. Fifteen electron beams were measured in four institutes according to the Belgian-Dutch code of practice for high-energy electron beams. The expanded uncertainty ($k = 2$) for the D_w values was 3.6% for a Roos chamber calibrated in ^{60}Co and 3.2% for a Roos chamber cross-calibrated against a Farmer chamber. The expanded uncertainty for the beam quality specifier, $R_{50,dos}$, was 0.14 cm. The audit acceptance levels were based on the expanded uncertainties for the comparison results and estimated to be 2.4%.

Results: The audit was implemented and validated successfully. All D_w audit results were satisfactory with differences in D_w values mostly smaller than 0.5% and always smaller than 1%. Except for one, differences in $R_{50,dos}$ were smaller than 0.2 cm and always smaller than 0.3 cm.

Conclusions: An electron dosimetry audit based on absorbed dose to water and present-day requirements for calibration laboratories performing proficiency tests was successfully implemented. It proved international traceability of the participants value with an uncertainty better than 3.6% ($k = 2$).

1. Introduction

External dosimetry audits are powerful quality assurance instruments for radiotherapy departments, allowing detection of potential systematic measurement errors [1,2]. In 2008 the Netherlands Commission on Radiation Dosimetry (NCS) issued a new Code of Practice (CoP) for high-energy photon and electron beams, NCS-18 [3], replacing the air-kerma based CoPs [4,5], based on the IAEA TRS-398 [6]. It focused on methods and equipment used in Belgium and the Netherlands. Differences between NCS-18 and TRS-398 are smaller than their combined uncertainties [3]. Most radiotherapy centres implemented NCS-18 for photon beams, but up to recently postponed doing so for electron beams. Therefore, the NCS decided to organize an electron beam dosimetry audit [7] similar to their photon audit [8]. The audit would become a service by VSL, the Dutch national metrology institute, under calibration and proficiency testing accreditations, i.e. ISO-17025 [9], and ISO-17043 [10].

Literature research revealed electron audits that were developed more than two decades ago [11–14], based on air-kerma CoPs while modern CoPs are based on absorbed dose to water. Currently, requirements for calibration laboratories and proficiency test have further developed [9,10] and were not considered in audits previously published.

The aim of this study was to implement an electron dosimetry audit based on absorbed dose to water with suitable acceptance criteria based on thorough uncertainty analyses, in agreement with present-day requirements for calibration laboratories performing proficiency tests, including correlations, which allows for increased sensitivity in detection of systematic errors.

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Table 1
Overview of the electron beams in this study for the four participating institutes. Here SSD is the Source Surface Distance and 'isoc' refers to the accelerator *iso*-centre.

Participant	Linear accelerator type	Nominal energies/MeV	SSD/cm	Field size at isoc[a]/ cm^2
A	Elekta Synergy (MLCi)	6; 12; 18	95	10.5 × 10.5
B	Elekta Synergy (Agility)	4; 10; 15	100	10.5 × 10.5
C	Varian TrueBeam	6; 9; 22	100	10 × 10
D	Elekta Synergy (MLCi)	4; 12 4 (HDRE)	100	10.5 × 10.5 42 × 42[b]

[a] Field size is 10 × 10 cm^2 defined by the applicator: Elekta accelerators at 95 cm; Varian at 100 cm.
[b] Field size of '4 (HDRE)' at *iso*-centre is fixed and larger than the surface area of the audit phantom.

2. Materials and methods

2.1. Audit protocol

The audit protocol fully implemented the requirements for proficiency tests and calibration laboratories according to ISO-17043 [10] and ISO-17025 [9] respectively. It contained the objective of the audit, the reference conditions and associated measurement uncertainties, leading to audit acceptance criteria. The subject of this audit was the determination of absorbed dose to water, D_w, at reference depth, z_{ref}, and the beam quality, specified by the 50% dose level beyond the dose maximum, $R_{50,dos}$, in high-energy electron beams. Four participating institutions performed their beam calibrations according to local procedures. The audit team performed on-site beam calibrations according to the procedures described in this study, with its own equipment on the same day. Table 1 summarizes the fifteen selected electron beams.

The audit was conducted as a comparison based on the difference between the beam calibrations of the participant, i.e. measured value, x, and by the audit team, i.e. measured reference value, X. All beam calibrations were performed at the participant's source surface distance, SSD, and field size (Table 1). This was done to avoid additional corrections to take account for differences in SSD and related errors. The result of the audit was expressed as an E_n-score and the outcome was either 'satisfactory' if $|E_n| \leq 1.0$ or 'unsatisfactory' if $|E_n| > 1.0$, according to ISO-17043 [10]:

$$E_n = \frac{\Delta}{U_\Delta} \tag{1}$$

where U_Δ was the acceptance criterion, agreed upon prior to the audit and in this study based on the expanded uncertainty of Δ:

$$\Delta = x - X \tag{2}$$

The audit result in the beam quality, $\Delta_{R50,dos}$ in cm, was expressed as an absolute value:

$$\Delta_{R_{50,dos}} = R_{50,dos} - R_{50,dos,ref} \tag{3}$$

The audit result in the absorbed dose, Δ_{Dw}, was expressed as a relative value:

$$\Delta_{D_w} = \frac{D_w - D_{w,ref}}{D_{w,ref}} \tag{4}$$

Combining Eqs. (1), (3) and (4) leads to:

$$E_{n,R_{50,dos}} = \frac{\Delta_{R_{50,dos}}}{U_{\Delta_{R_{50,dos}}}} \tag{5}$$

and

$$E_{n,D,w} = \frac{\Delta_{D_w}}{U_{\Delta_{D,w}}} \tag{6}$$

$U_{\Delta,R50,dos}$, in cm, and $U_{\Delta Dw}$, in% were the expanded uncertainties and thus the acceptance criteria for the audit results in $R_{50,dos}$ and D_w respectively.

After setting up the audit equipment percentage depth ionization, PDI, curves and D_w were measured with a plane-parallel Roos chamber (PTW-34001, PTW Freiburg GmbH, Freiburg, Germany), calibrated in terms of D_w for ^{60}Co. For an electron beam with beam quality $R_{50,dos} > 7$ cm a cross-calibration of the Roos chamber against a cylindrical Farmer chamber (NE2571, Phoenix Dosimetry Ltd, Sandhurst, UK) was performed at the highest energy, as required by NCS-18 protocol, because of its reduced uncertainty in D_w compared to that with a ^{60}Co calibrated plane-parallel chamber. The audit team's D_w measurements were repeated after the participant's measurements. Temperature and pressure were monitored during the whole comparison session; chamber readings were corrected to reference temperature and pressure.

2.2. Water phantom and positioning

The audit team used a water phantom (PTW-MP1-T41025) with dimensions of 32 × 37 × 32 cm^3 ($L \times W \times H$) and PMMA wall thickness of 1 cm with an automated vertical translation stage. The waterproof Roos chamber was placed in the centre of the phantom, which was placed on the patient couch. The source to water surface distance, SSD, was determined according to the local method to avoid discrepancies in dose measurement due to geometric measurements.

2.3. Measurement of $R_{50,dos}$ and determination of z_{ref}

The reference depth for the D_w measurement, z_{ref}, was determined according to Eq. (9) in NCS-18 [3], based on the beam quality specifier, $R_{50,dos}$:

$$z_{ref} = 0.6 R_{50,dos} - 0.1 \tag{7}$$

$R_{50,dos}$ was determined twofold: first it was based on $R_{50,ion}$, measured with the Roos chamber and converted to $R_{50,dos}$. $R_{50,ion}$ was defined as the depth beyond the dose maximum, where the PDI had a value of 50%. Second, $R_{50,dos}$ was determined from the percentage depth dose curve, PDD, converted from PDI to PDD as described by Andreo et al. [6]. Differences between the two methods were smaller than 0.03 cm thus considered insignificant.

All PDIs except the '4 (HDRE)' beam at participant D were measured with a beam size close to 10 × 10 cm^2 despite the recommended use of 20 × 20 cm^2 fields at the higher electron energies with $R_{50,dos} > 7$ cm. The effect of potential insufficient scatter on the determination of $R_{50,dos}$ at 10 × 10 cm^2 [15] was measured for 10 × 10 cm^2 and 20 × 20 cm^2 beams at participant C (22 MeV) and found to be insignificant (i.e. < 0.04 cm) with respect to the uncertainties in this study. Changes of the chamber's polarity correction, k_{pol}, with depth between $R_{100,ion}$ and $R_{50,ion}$ were considered negligible, as well as the variation in stem effect close to the PDD 50% point. Ion recombination is known to depend on the dose per pulse and thus varies with depth. k_s was not measured at each depth, however it was determined at depth by assuming a proportional relation between the corrected chamber signal and the fraction of incomplete charge collection (i.e. $k_s - 1$). This was based on the k_s measurement at z_{ref}, neglecting initial recombination. It was taken into account by an additional standard uncertainty of 0.003 cm in the uncertainty for $R_{50,dos}$ based on the chosen method compared to if charge measurements would have been done to determine k_s at all depths with an uncertainty of 0.1% as applied for k_s (see also Section 2.5 and Table A1). During the PDI measurements a monitor ion chamber (PTW-31013 Semiflex) was mounted at the edge in the beam read out simultaneously with the Roos chamber while the translation stage moved stepwise in vertical direction upwards.

2.4. Determination of D_w

The absorbed dose to water, D_w, in electron beam quality Q was measured using the Roos chamber connected to an electrometer (PTW-UNIDOS-T10002) and obtained according to [3]:

$$D_{w,Q} = M_{corr}^{PP} N_{D,w,Q}^{PP} \quad (8)$$

where $M_{corr}{}^{PP}$ is the corrected electrometer reading and $N_{D,w,Q}{}^{PP}$ is the chamber calibration coefficient in beam quality Q, based on a ^{60}Co calibration, $N_{D,w,Q0}{}^{PP}$, with beam quality correction $k_{Q,Q0}{}^{PP}$ taken from [3].

$$N_{D,w,Q}^{PP} = N_{D,w,Q_0}^{PP} k_{Q,Q_0}^{PP} \quad (9)$$

A cross-calibration of the Roos chamber was done with a Farmer chamber in a high-energy electron beam with a beam quality Q with value $R_{50,dos} > 7$ cm, if this beam was part of the audit:

$$N_{D,w,Q}^{PP} = \left\{ \frac{M_{QCROSS}^{CYL}}{M_{QCROSS}^{PP}} N_{D,w,Q_0}^{CYL} k_{Qcross,Q_0}^{CYL} \right\} k_{Q,QCROSS}^{PP} \quad (10)$$

The term between brackets represents the cross-calibration procedure [3] and was obtained by the charge measurements $M_{Qcross}{}^{PP}$ and $M_{Qcross}{}^{CYL}$ with both chambers' EPOMs subsequently positioned at z_{ref}. For the Farmer chamber the EPOM was 0.158 cm above its geometrical centre. The Farmer chamber was placed inside a 1 mm waterproof PMMA sleeve and latex sleeve to keep it dry. The bias voltages of the Roos and Farmer chamber were set to +200 V and +300 V respectively. The corrected electrometer reading for the chambers, M_{corr}, was obtained by:

$$M_{corr} = M\, k_{elec}\, k_{pT}\, k_s\, k_{pol} \quad (11)$$

where the raw electrometer reading, M, was corrected for electrometer calibration, k_{elec}. The air cavity density was corrected to reference air density based on the ambient pressure and temperature, k_{pT}. Further corrections were applied for recombination, k_s and chamber polarity, k_{pol}. Chamber leakage was measured but small enough to be neglected (< 0.05%). A humidity correction, k_h, was not applied since the chamber calibration coefficient was applicable at a humidity between 20% and 80% for which the ionization chamber response varies less than 0.1% [16,17]. Furthermore, no correction was applied for dose averaging over the chamber volume caused by beam radial non-uniformity, k_{rn}, as it is not addressed by the code of practice applied in this study and therefore inherently part of the ion chambers k_Q, more specifically the chamber overall perturbation factor k_p as described by e.g. Andreo et al. [6].

2.5. Uncertainties in $R_{50,dos}$ and D_w

The standard uncertainties, u, were determined in accordance with the Guide to the expression of Uncertainty in Measurement, GUM, [18] and converted to expanded uncertainties by multiplying with a coverage factor $k = 2$, with a coverage probability of approximately 95%. In this study, the uncertainties are expressed as type B expanded uncertainties, unless mentioned otherwise. Uncertainties are expressed in 2 significant digits with a minimum resolution of 0.01% or 0.01 cm.

It is unusual for radiotherapy centres to report uncertainties. Due to the used methods and instruments, it was likely that the participant's final uncertainties were similar as those of the audit team and for simplicity they were considered to be the same.

The uncertainty for $R_{50,dos}$ was 0.14 cm (Table A1). The associated uncertainty in z_{ref} was estimated to be 0.08 cm (Eq. (7)). For $R_{50,dos}$ relative uncertainties in charge measurements were converted to cm with a sensitivity coefficient of −0.03 cm %$^{-1}$ conservatively based on a PDD of −4% mm^{-1} for 22 MeV at a depth of $R_{50,dos}$. The uncertainty for $R_{50,dos}$ was composed of the PDI, the conversion from PDI to PDD based on stopping power ratios, $s_{w,air}$, and positioning of the Roos chamber.

The uncertainty for a single charge measurement of any chamber, M_{corr}, was 0.74% (Table A2). This uncertainty, used for the uncertainty in D_w, was dominated by (re-)positioning of the chamber at SSD and z_{ref}. The uncertainty due to the depth was based on a PDD of −0.4% mm^{-1} for 22 MeV at z_{ref}. Furthermore, the electrometer calibration, long-term drift and display resolution were considered. Uncertainties for k_{pT} were dominated by the thermometer calibration and the estimated measured temperature difference with that of the ionization chamber. Beam output fluctuations between the audit and participant's measurements, usually performed within a couple of hours following each other, were assumed to be negligible.

The uncertainty for D_w measured with a Roos or Farmer chamber was 3.6% and 2.8% respectively (Table A3). The contribution of $R_{50,dos}$ and conversion from PDI to PDD using stopping power ratios was incorporated in the uncertainty of $k_{Q,Q0}$ (see e.g. [3] and [6]). Note that the reported uncertainty for D_w measured with a Farmer chamber was only valid in high-energy beams with $R_{50,dos} > 7$ cm. The uncertainty for D_w measured with a cross-calibrated plane parallel chamber was 3.2% (Table A4).

2.6. Uncertainties and acceptance criteria in the audit results $\Delta_{R50,dos}$ and Δ_{Dw}

The uncertainty on the audit result $\Delta_{R50,dos}$, Eq. (3), expressed as $U_{\Delta R50,dos}$, is 0.20 cm. It was determined by the quadratic summation of the reference value and participant uncertainties, $U_{R,50,dos} = 0.14$ cm (Table A1) since no correlations exist between the reference value and participant's value.

The expanded uncertainty on the audit result $\Delta_{D,w}$, Eq.s (4) and (6), expressed as $U_{\Delta Dw}$, is 2.4% for both a ^{60}Co calibrated (Table A5) and cross-calibrated Roos chamber (Table A6). Correlations between the D_w values of the audit team and by the participant were considered, which are: traceability to VSL, applied dosimetry protocol and k_Q dataset. Therefore, some uncertainty contributions could be neglected. This was implemented in the following way. Uncertainty contributions for fully uncorrelated quantities were indicated with 'audit' in Tables A2–4 and transferred to Tables A5 and A6. For the uncertainty contribution of partially correlated input quantities (calibration coefficients and k_Q) in Tables A3 and A4, only the uncorrelated part was added to Tables A5 and A6: i.e. long-term (< 3 year) chamber $N_{D,w,Q0}$ and chamber-to-chamber $k_{Q,Q0}$ variation. The magnitude of the Roos $k_{Q,Q0}$ variation depends on the origin of the calibration coefficient in electron beam quality Q: i.e. calibrated in ^{60}Co (Table A3) or cross-calibrated in an electron beam (Table A4). For Roos chambers calibrated in ^{60}Co the chamber-to-chamber variation was caused by a variation in pwall in ^{60}Co and the uncertainty related to other perturbation corrections, p_Q [3,6]. Due to a lack of information about the uncertainties responsible for chamber-to-chamber $k_{Q,Q0}$ variation of these chambers, a standard uncertainty contribution of 1.0% was used, representing variations of $k_{Q,Q0}$ between the audit and participant's chamber (Table A5). A similar approach was applied with respect to the audit result obtained with the Farmer chamber which has smaller $k_{Q,Q0}$ variations due to a better understanding of their perturbation corrections, taken to be 0.5% [3,6] (Table A6).

3. Results

The outcome of the audits was for all fifteen beams 'satisfactory' with E_n-scores well below unity (Table 2 and Fig. 1), both for results obtained with the plane-parallel's ^{60}Co calibration and with its cross-calibration in a high-energy electron beam when available. The difference in dose based on a ^{60}Co calibrated chamber, ΔD_w, ranged between −1.0% and +0.9% with an average of −0.2% and a standard deviation of 0.5%. For cross-calibrated value these results were similar with an average for ΔD_w of +0.1% and a standard deviation of 0.5% (see Table A7).

Table 2
Audit results for $R_{50,dos}$ and D_w in fifteen electron beams at the four participating institutes of this study. Cross-calibration results are only reported for institutes where beams were available with $R_{50,dos} > 7$ cm (last two columns).

Participant (Table 1)	E/MeV	$R_{50,dos}$		D_w with the Roos chamber				
				^{60}Co-calibration			Cross-calibration	
		$\Delta_{R50,dos}$/cm	E_n-score	Δ_{Dw}/%	E_n-score	Overall audit result[a]	Δ_{Dw}[a]/%	E_n-score[a]
A	6	0.09	0.5	−0.52	0.2	satisfactory	0.40	0.2
	12	0.11	0.6	−0.51	0.2	satisfactory	0.42	0.2
	18	0.15	0.8	−0.55	0.2	satisfactory	0.38	0.2
B	4	−0.02	0.1	0.09	0.0	satisfactory	–	–
	10	0.01	0.1	0.42	0.2	satisfactory	–	–
	15	0.27	1.4	−0.20	0.1	satisfactory	–	–
C	6	−0.01	0.1	0.02	0.0	satisfactory	−0.30	0.1
	9	−0.03	0.2	0.28	0.2	satisfactory	−0.04	0.0
	22	0.03	0.2	0.08	0.0	satisfactory	−0.23	0.1
D	4	−0.01	0.1	0.14	0.1	satisfactory	–	–
	4 (HDRE)	0.02	0.1	0.90	0.4	satisfactory	–	–
	12	0.14	0.7	−0.39	0.2	satisfactory	–	–
A	6	−0.03	0.2	−0.43	0.2	satisfactory	−0.34	0.1
	12	0.02	0.1	−0.69	0.3	satisfactory	−0.59	0.3
	18	0.10	0.5	−1.0	0.4	satisfactory	−0.94	0.7

[a] Values obtained using the Roos chamber cross-calibrated in a high-energy electron beam.

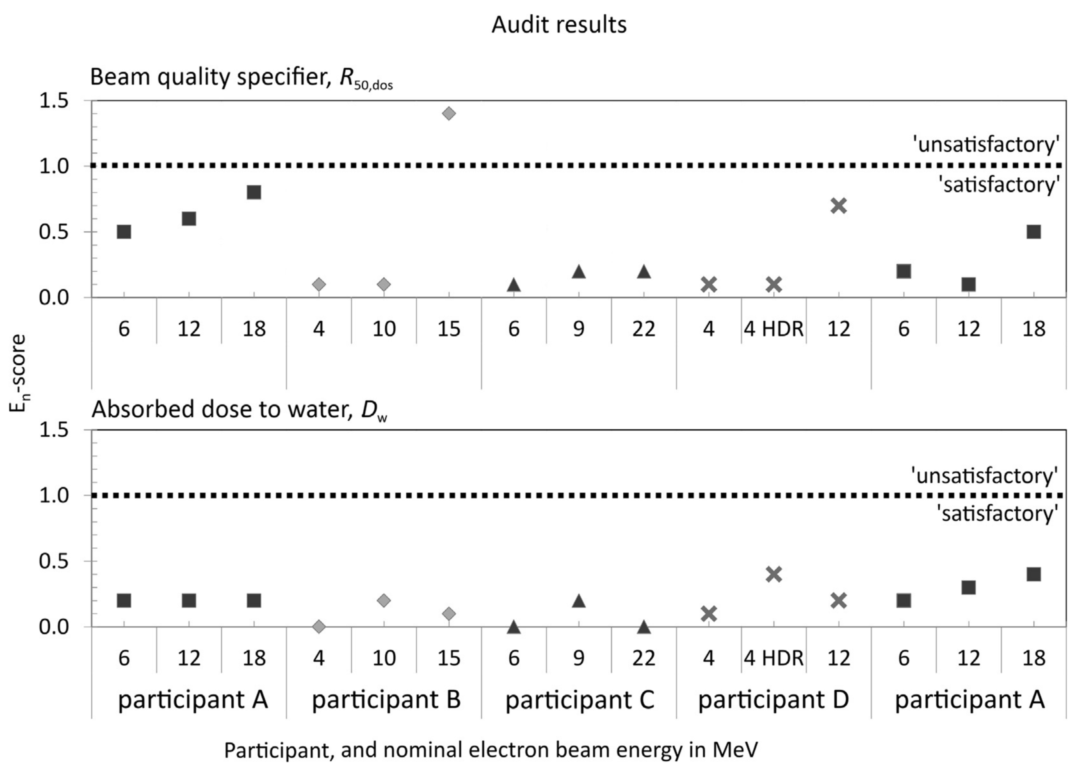

Fig. 1. Audit results in the fifteen electron beams of the four participants for beam quality specifier, $R_{50,dos}$ (top) and absorbed dose to water, D_w (bottom). The horizontal dotted lines mark the separation between 'unsatisfactory' audit results ($|En| > 1$) and 'satisfactory' audit results ($|En| \le 1.0$).

All audit D_w values were measured traceable to internationally accepted measurement standards with an uncertainty of 3.6% or better ($k = 2$). The smallest uncertainty of 2.8% was achieved with a Farmer chamber, but only for high-energy electron beams with $R_{50,dos} > 7$ cm. For all other beam qualities, it was 3.2% for a cross-calibrated Roos chamber. The third, least accurate option was much simpler and time efficient, where D_w was obtained with a ^{60}Co calibrated Roos chamber with an uncertainty of 3.6% (k = 2). In this study, the uncertainty on the audit result based on a ^{60}Co calibrated Roos chamber or a cross-calibrated Roos chamber was estimated to be the same, i.e. 2.4% ($k = 2$).

For all beams expect one, the E_n-scores for $R_{50,dos}$ were smaller than unity. The average difference between the $R_{50,dos}$ values obtained by the institute and by the audit team was 0.1 cm with a standard deviation of 0.1 cm. The largest deviation of $R_{50,dos}$ was 0.3 cm for the participant B 15 MeV beam, which resulted in an E_n-score of 1.4. Despite this, there was no significant effect observed for D_w audit value here and the audit result was considered 'satisfactory'.

The audit D_w measurements with a ^{60}Co calibrated and cross-calibrated Roos chamber generally agreed within 0.4% except for results of the first audit at participant A.

4. Discussion and conclusion

For all beams measured in this study ‘satisfactory’ audit results were obtained, based on the uncertainties, i.e. all participant’s D_w value agreed within 1% with the reference value in relation to an estimated uncertainty on the audit result of 2.4% (k = 2). Despite this, during the first audit at participant A, the audit team’s D_w value based on a ^{60}Co-calibration showed a discrepancy of approximately 1% compared to its cross-calibration based value. After further investigation, it was concluded that this was caused by a wrong alignment of the Famer chamber at its EPOM during the cross-calibration. Unfortunately, the E_n-scores on either of the results, i.e. ^{60}Co-based or cross-calibration based, didn’t reveal this discrepancy.

The uncertainty assigned in this study to the D_w measurement is 3.2% (k = 2) when based on a cross-calibrated Roos chamber in a high-energy beam and 3.6% (k = 2) when based on a ^{60}Co calibrated Roos chamber. This uncertainty shows an improvement compared to the uncertainty budgets proposed by NCS-18 [3], respectively 3.6% and 4.0% (k = 2). It also shows an improvement compared to the electron dosimetry up to 1990, based on air-kerma protocols with uncertainties between 5.6% and 7.4% (k = 2) [19]. Thomas et al. [2] has presented the long-term results of reference dosimetry audits in the UK using the IPEM CoPs, which included absorbed dose to water based methods. The presented results in Thomas et al. showed to be consistent with the current study. However, the current study applied acceptance criteria which is based on thorough uncertainty analyses for both the reference and participant values. Due to the same traceability route to primary dosimetry standards and the same CoP. Correlations were included in the uncertainty analysis.

If the current audit would be performed at participants that are not traceable to VSL or that apply different dosimetry protocols then uncertainty budgets or the applied methods and traceability route needs adjustment. Moreover, if the current methods and traceability route would be applied, comparisons with older dosimetry audits is hardly possible since they generally lack a prospective uncertainty analysis to determine realistic uncertainties and related acceptance criteria. This would lead to posterior acceptance criteria based on historical differences instead of well-defined measurement uncertainties.

In conclusion: this study described the implementation of an electron dosimetry audit based on absorbed dose to water and on present-day requirements for calibration laboratories when performing proficiency tests. Acceptance criteria are based on a detailed uncertainty budget when applying a contemporary absorbed dose to water based CoP. The agreement with audit team’s measurement at the day of the audit proved traceability of the participants value traceable to internationally accepted measurement standards through an unbroken chain of calibrations. The uncertainty assigned to this measurement is better than 3.6% (k = 2).

5. Disclaimer

Identification of certain commercial equipment, instruments, or materials are identified in this study to specify the experimental procedure adequately. Such identification does not imply recommendation or endorsement by the authors or the NCS, nor does it imply that products identified are necessarily the best available for purpose.

Appendix A

This appendix contains the supporting uncertainty budget, presented in tables as used and referred to in the main text. All uncertainty contributions are of type B unless mentioned otherwise. The final table presents the measurement results of this study. The expanded uncertainty used in this comparison is pressed bold.

Table A1
Uncertainty budget for determination of $R_{50,dos}$ in cm. Uncertainties in charge measurements are converted to depth with a sensitivity coefficient of $-0.03\ \mathrm{cm}\ \%^{-1}$.

Source of uncertainty	Standard uncertainty /cm
alignment and positioning of Roos chamber	0.05
calibration of vertical translation stage	0.04
beam energy change between measurement and audit (max. 1% output at $R_{50,dos}$)[a]	0.03
ratio of charge measurements at PDI_{max} and at $PDI_{50\%}$ (u = 0.1%)	0.003
depth dependent correction for recombination, k_s (u < 0.1%)	0.003
depth dependent correction for chamber polarity, k_{pol} (u < 0.1%)	0.003
variation of T and p during a PDI measurement, k_{pT} (u < 0.2%)	0.006
PDI to PDD conversion [6] (u = 0.2%)	0.006
combined standard uncertainty, u (k = 1)	0.07
expanded uncertainty, U (k = 2)	**0.14**

[a] Participant’s measurement and audit measurement were not performed on the same day.

Table A2
Uncertainty for the determination of a corrected electrometer reading, M_{corr} with an ion chamber at a depth of z_{ref}, applicable for both Roos and Farmer chambers. Uncertainties in positioning at depth are converted to dose with a sensitivity coefficient of $-0.4\%\ mm^{-1}$.

Source of uncertainty	Standard uncertainty /%
repeated charge measurement (type A)	0.10
SSD (u = 0.1 cm at an SDD of 100 cm)	0.20
positioning of ionization chamber in water at z_{ref} (u = 0.05 cm)	0.20
electrometer calibration, long term drift and resolution	0.07
k_{pT}: correction for ambient temperature and pressure	0.10
k_h: variation of relative humidity (20–80%)	0.05
k_s: correction for ion recombination	0.10
k_{pol}: polarity correction	0.10
k_{rn}: variation due to beam radial non-uniformity	0.10
combined standard uncertainty (k = 1)	0.37
expanded uncertainty, U (k = 2)	**0.74**

Table A3
Measurement of D_w at a depth of z_{ref}, based on a Roos and Farmer chamber calibrated in ^{60}Co. Uncertainties indicated with 'audit' contribute to the audit result.

Source of uncertainty		Roos chamber u /%	Farmer chamber u/%
M_{corr}: corrected charge measurement at z_{ref} (Table A2)	**audit**	0.37	0.37
$N_{D,w,Q0}$: chamber calibrated in ^{60}Co		0.50	0.50
$k_{Q,Q0}$: chamber quality correction [3]		1.70	1.2
uncertainty of $R_{50,dos}$ on $k_{Q,Q0}$ (0.07 cm)	**audit**	0.09	0.09
combined standard uncertainty (k = 1)		1.8	1.4
expanded uncertainty (k = 2)		**3.6**	**2.8**
combined standard uncertainty contribution to audit result, based on contributions indicated with 'audit' only (k = 1)	**audit**	0.38	0.38

Table A4
Measurement of D_w at a depth of z_{ref}, based on a Roos chamber cross-calibrated against a Farmer chamber. Uncertainties indicated with 'audit' contribute to the audit result.

Source of uncertainty		u/%
D_w at $R_{50,dos}$ > 7 cm with a Farmer chamber (Table A3)		1.35
M_{corr}: corrected charge measurement at $R_{50,dos}$ > 7 cm (Table A2)	**audit**	0.35
M_{corr}: corrected charge measurement at beam quality Q (Table A2)	**audit**	0.35
$k_{Q,Qcross}$: Roos chamber quality correction [3]		0.60
influence of measurement of $R_{50,dos}$ on Roos $k_{Q,Qcross}$	**audit**	0.09
combined standard uncertainty (k = 1)		1.6
expanded uncertainty (k = 2)		**3.2**
combined standard uncertainty contribution to audit result, based on contributions indicated with 'audit' only (k = 1)	**audit**	0.50

Table A5
The uncertainty budget for the audit results $\Delta_{D,w}$ in D_w at beam quality Q with a Roos chamber calibrated in ^{60}Co.

Source of uncertainty	Standard uncertainty /%
reference D_w value, correlations taken into account ('audit' in Table A3)	0.38
participants D_w value, correlations taken into account ('audit' in Table A3)	0.38
long-term (< 3 year) variation of participant's $N_{D,w}$	0.15
$k_{Q,Q0}$ individual chamber variation for Roos chambers	1.0
combined standard uncertainty (k = 1)	1.2
expanded uncertainty (k = 2)	2.4

Table A6
The uncertainty budget for the audit results $\Delta_{D,w}$ in D_w at beam quality Q with a Roos chamber cross-calibrated in Q_{cross} with $R_{50,dos} > 7$ cm.

Source of uncertainty	Standard uncertainty /%
reference D_w value at Q_{cross}, correlations taken into account ('audit' in Table A4)	0.38
participants D_w value at Q_{cross}, correlations taken into account ('audit' in Table A4)	0.38
long-term (< 3 year) variation of participant $N_{D,w}$ for a Farmer chamber in ^{60}Co	0.15
$k_{Q,Q0}$ individual chamber variation for Farmer chambers	0.50
reference D_w value at Q, correlations taken into account ('audit'in Table A5)	0.50
participants D_w value at Q, correlations taken into account ('audit'in Table A5)	0.50
$k_{Q,Q0}$ individual chamber variation for Roos chambers	0.50
combined standard uncertainty (k = 1)	1.2
expanded uncertainty (k = 2)	2.4

Table A7
Reference values and participants' values during the audit.

Participant (Table 1)	E/MeV	Reference value				Participants' value		
		$R_{50,dos}$/cm	z_{ref}/cm	D_w/cGy	D_w[a]/cGy	$R_{50,dos}$/cm	z_{ref}/cm	D_w/cGy
A	6	2.54	1.42	199.4	197.6	2.63	1.48	198.4
	12	4.88	2.83	200.8	198.9	4.99	2.89	199.7
	18	7.20	4.22	197.1	195.3	7.35	4.31	196.1
B	4	1.62	0.87	197.1	–	1.60	0.86	197.3
	10	3.99	2.29	196.0	–	4.00	2.30	196.8
	15	6.00	3.50	196.0	–	6.27	3.66	195.6
C	6	2.39	1.34	304.8	305.8	2.38	1.33	304.8
	9	3.63	2.08	296.1	297.0	3.60	2.06	296.9
	22	8.75	5.15	286.5	287.4	8.78	5.17	286.8
D	4	1.61	0.86	199.3	–	1.60	0.86	199.6
	4 (HDRE)	1.58	0.85	200.9	–	1.60	0.86	202.7
	12	4.64	2.69	200.0	–	4.78	2.77	199.3
A	6	2.55	1.43	199.6	199.4	2.51	1.41	198.7
	12	4.93	2.86	198.8	198.6	4.95	2.87	197.4
	18	7.22	4.24	197.4	197.2	7.32	4.29	195.4

[a] Values obtained using the Roos chamber cross-calibrated in a high-energy electron beam.

Conflict of interest

The authors declare there are no conflicts of interest.

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