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Impact of electrometer sensitivity variation on absorbed dose-to-water determination: a multicenter uncertainty study

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Research Article

Keywords: absorbed dose to water, uncertainty, electrometer calibrated, electrometer sensitivities

Posted Date: June 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10038409/v1

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Additional Declarations: No competing interests reported.

Title : Impact of electrometer sensitivity variation on absorbed dose-to-water determination: a multicenter uncertainty study

Manuscript type：**Original Paper**

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KEYWORDS: absorbed dose to water, uncertainty, electrometer calibrated, electrometer sensitivities

Background: Accurate absorbed dose-to-water determination in radiotherapy requires electrometers calibrated by a primary standards laboratory (PSL). Recent studies have suggested that electrometers of the same model may exhibit sufficiently similar sensitivity characteristics to allow the use of a common electrometer calibration coefficient for quality-control purposes. However, the effect of this approach on absorbed dose-to-water uncertainty has not been quantitatively evaluated.

Purpose: To evaluate the uncertainty contribution associated with the use of a common electrometer calibration coefficient and to assess its influence on absorbed dose-to-water determination. Methods A multicenter study was conducted involving 12 radiotherapy facilities and 24 combinations of linear accelerators, ionization chambers, and electrometers. All electrometers possessed valid PSL-issued calibration coefficients. Absorbed dose-to-water values were calculated using both the PSL calibration coefficient (k_{elec}) and a common electrometer coefficient ($k_{elec,user}$). Dose monitor unit values and uncertainty budgets were compared for 6-MV and 10-MV photon beams. Uncertainty analysis was performed according to the Guide to the Expression of Uncertainty in Measurement (GUM).

Results: Only small differences were observed between dose monitor unit values calculated using (k_{elec}) and ($k_{elec,user}$). The user-dependent uncertainty increased from 0.17% to 0.23% (k = 1), corresponding to an increase of approximately 0.06 percentage points. However, this contribution remained substantially smaller than the dominant uncertainty sources in reference dosimetry. Consequently, the combined standard uncertainty and expanded uncertainty of absorbed dose-to-water determination remained unchanged.

Conclusion: The uncertainty contribution associated with the common electrometer calibration coefficient was small and had no meaningful influence on the overall uncertainty budget of absorbed dose-to-water determination. These findings support the use of a common coefficient for electrometer sensitivity verification and quality-control applications within a given electrometer type. Although periodic PSL calibration remains essential for maintaining traceability, common-coefficient-based verification may provide a useful complementary approach for routine electrometer quality assurance.

1 INTRODUCTION

To use medical linear accelerators, the absorbed dose delivered to patients must be determined according to established dosimetry protocols such as AAPM TG-51[1] and IAEA TRS-398.[2] In these protocols, the absorbed dose to water is calculated from the charge collected in an ionization chamber and measured with an electrometer. The absorbed dose-to-water calibration coefficient, $N_{D,w}$, and electrometer calibration coefficient, k_{elec}, are provided by a primary standards laboratory (PSL) and constitute essential components of the traceability chain for reference dosimetry.[3, 4] Periodic verification of electrometer performance is also recommended to ensure the stability and reliability of dose measurements. [5]

Electrometer quality control can be performed using either an ionization chamber irradiated in a radiation beam or a dedicated current source. The former method is affected by variations in accelerator output and chamber response, whereas the latter can provide a stable electrical signal with reduced measurement uncertainty.[6] However, commercially available precision current sources are often expensive and are not routinely available in many radiotherapy departments. To address this limitation, we developed a compact battery-powered current source based on a dry-cell battery, which has been patented in Japan.[7] Previous studies demonstrated that this device enables efficient verification of electrometer performance[8] and can be used for comparison of electrometer sensitivities.[9]

Recently, Tsuno et al.[9] reported a method for deriving a user-level electrometer sensitivity coefficient through comparison of electrometers using the developed current source. In that study, the variability of the derived coefficient was approximately 0.20%, suggesting that the current source may be useful for routine quality control and sensitivity verification. However, although the variability of the coefficient has been quantified, its impact on absorbed dose-to-water determination has not been evaluated. In particular, it remains unclear whether the use of a user-derived electrometer sensitivity coefficient introduces a measurable contribution to the overall uncertainty budget of absorbed dose-to-water measurements.

The uncertainty associated with absorbed dose-to-water determination is of fundamental importance because it directly affects the accuracy and traceability of reference dosimetry. Several studies have investigated uncertainty components in reference dosimetry systems.[10-14] Castro et al. reported uncertainty estimates for individual parameters used in absorbed dose-to-water measurements and showed that major contributions arise from factors such as the beam quality conversion coefficient, $k_{Q,Q0}$.[15] In contrast, the contribution of electrometer calibration coefficients has generally been regarded as small.[15] Nevertheless, quantitative evaluation of the uncertainty contribution associated with user-derived electrometer sensitivity coefficients has not been reported.

Another unresolved issue is whether the observed variability remains negligible under a range of clinically relevant measurement conditions. Previous studies of the SCG002 current source were primarily focused on the characterization of the current source itself and on electrometer sensitivity comparison.[8, 9] The practical implications of the reported coefficient variability for absorbed dose-to-water measurements across different institutions, electrometers, ionization chambers, and accelerator systems have not yet been investigated.

Therefore, the purpose of this study was to evaluate the uncertainty contribution of a user-derived electrometer sensitivity coefficient obtained from previously reported SCG002 measurements. Using measurement data collected from multiple radiotherapy institutions, we assessed the impact of the reported coefficient variability on absorbed dose-to-water determination and compared it with the uncertainty obtained using conventional PSL-calibrated electrometer coefficients. The results provide quantitative evidence regarding the significance of electrometer sensitivity variations within the overall uncertainty budget of reference dosimetry.

2 METHODS

2.1 Participating institutions and dosimetry systems

This multicenter study included measurements from 12 radiotherapy facilities. The linear accelerators used were TrueBeam (Varian Medical Systems, Palo Alto, CA), Clinac iX (Varian), Clinac 21EX (Varian), Versa HD (Elekta, Stockholm, Sweden), and Synergy (Elekta), resulting in 24 combinations of linear accelerators, ionization chambers, and electrometers.

A TN30013 Farmer-type ionization chamber (PTW, Freiburg, Germany) was used at all facilities. The electrometers included UNIDOS Tango and UNIDOS Webline (PTW), and RAMTEC Pro, RAMTEC Duo, and RAMTEC Solo (Toyo Medic, Tokyo, Japan).

All electrometers possessed valid calibration coefficients issued by a primary standards laboratory (PSL). No electrometer calibration was performed using the SCG002 current source as part of the present study. Absorbed dose-to-water measurements were performed using 6-MV and 10-MV photon beams under reference conditions according to the AAPM TG-51 protocol.[1] The measured absorbed dose-to-water values were subsequently converted to dose monitor unit (DMU) values for intercomparison.

The participating institutions employed different combinations of linear accelerators and electrometers, allowing assessment of the practical influence of electrometer calibration coefficients under a range of clinically relevant dosimetry conditions.

2.2 User-derived electrometer calibration coefficient

Tsuno et al. [9] investigated electrometer sensitivity verification using the SCG002 battery-powered current source. Their study demonstrated that electrometers of the same model exhibited only small differences in sensitivity and suggested that a common user-derived electrometer calibration coefficient ($k_{elec,user} \approx 1.000$) could potentially be shared among electrometers of the same type.

The present study did not experimentally determine $k_{elec,user}$. Instead, previously published data reported by Tsuno et al.[9] were incorporated into the analysis.

To investigate the dosimetric implications of this concept, absorbed dose-to-water values were calculated using both:

1. the PSL-provided electrometer calibration coefficient (k_{elec}), and
2. a user-derived coefficient (kelec,user ≈ 1.000).

The purpose of this comparison was to determine whether replacing institution-specific PSL calibration coefficients with a common user-derived coefficient would materially affect absorbed dose-to-water determination.

2.3 Calculation of absorbed dose to water

The corrected electrometer reading, M, was calculated as

$$M = M_{\mathrm{raw}} k_{\mathrm{TP}} k_{\mathrm{s}} k_{\mathrm{pol}} k_{\mathrm{elec}} \qquad (1)$$

where $M_{\mathrm{raw}}$is the raw electrometer reading, $k_{\mathrm{TP}}$is the temperature-pressure correction factor, $k_{\mathrm{s}}$is the ion recombination correction factor, $k_{\mathrm{pol}}$is the polarity correction factor, and $k_{\mathrm{elec}}$is the electrometer calibration coefficient.

The absorbed dose to water at the reference depth was calculated as

$$D_{\mathrm{w}}(d_{\mathrm{ref}}) = M N_{\mathrm{D,w}} k_{\mathrm{Q}} \qquad (2)$$

where $N_{\mathrm{D,w}}$is the absorbed dose-to-water calibration coefficient and $k_{\mathrm{Q}}$is the beam quality conversion coefficient.

For comparison, Eq. (1) was evaluated using both k_{elec} and $k_{elec,user}$.

The absorbed dose-to-water values were converted to DMU values as

$$DMU = \frac{D_w(d_c)}{TMR(d_c, 10 \times 10) \times MU}\,[\mathrm{cGy/MU}] \qquad (3)$$

where $TMR(d_c, 10 \times 10)$is the tissue maximum ratio at the calibration depth and $MU$is the monitor unit setting used at each institution.

The resulting values are denoted as $DMU_{elec}$and $DMU_{elec,user}$, respectively.

2.4 Uncertainty analysis

Measurement uncertainty was evaluated in accordance with the Guide to the Expression of Uncertainty in Measurement (GUM).

The uncertainty components considered in this study were:

- raw electrometer reading (M_{raw}),
- temperature-pressure correction factor (k_{TP}),
- polarity correction factor (k_{pol}),
- ion recombination correction factor (k_{s}),
- absorbed dose-to-water calibration coefficient ($N_{\mathrm{D,w}}$),
- beam quality conversion coefficient (k_{Q}), and
- electrometer calibration coefficient (k_{elec}).

Two uncertainty models were evaluated:

1. conventional reference dosimetry using the PSL-provided coefficient (k_{elec});
2. reference dosimetry using the common user-derived coefficient ($k_{elec,user}$) proposed by Tsuno et al.[9].

The objective of the uncertainty analysis was to quantify the contribution of replacing k_{elec} with $k_{elec,user}$ within the overall absorbed dose-to-water uncertainty budget.

The same uncertainty model was applied to all participating institutions because the purpose of the study was to evaluate the general influence of the electrometer coefficient substitution rather than to derive institution-specific uncertainty estimates.

The uncertainty equations used in the analysis are summarized in Table 1, and detailed derivations are provided in Appendix A.

3 RESULTS

3.1 Comparison of DMUelec and DMUelec,user

To evaluate the practical effect of replacing the PSL-provided electrometer calibration coefficient (k_{elec}) with a common user-derived coefficient ($k_{elec,user}$), DMU values calculated using both coefficients were compared.

Figure 1 shows the distributions of DMU_{elec} and $DMU_{elec,user}$ for 6-MV photon beams. The mean ± SD values were 1.003 ± 0.0044 and 1.002 ± 0.0046, respectively. The corresponding coefficients of variation (CVs) were 0.44% and 0.46%.

Figure 2 shows the corresponding results for 10-MV photon beams. The mean ± SD values were 1.002 ± 0.0044 and 1.002 ± 0.0045, respectively, with CVs of 0.44% and 0.45%. For both beam qualities, the distributions obtained using k_{elec} and $k_{elec,user}$ were nearly identical, and all values remained within ±1.5%.

3.2 Uncertainty analysis

The uncertainty components associated with k_{TP}, k_{pol}, and k_s are summarized in Table 1. The uncertainty contribution from k_{TP} was 0.031%, consisting of uncertainties associated with water temperature and atmospheric pressure measurements. The uncertainty contributions from k_{pol} and k_s were 0.073% and 0.11%, respectively. Detailed derivations of the uncertainty propagation equations are provided in Appendix A.

3.3 Uncertainty of absorbed dose-to-water determination

Table 2 summarizes the uncertainty budgets for absorbed dose-to-water determination.Two uncertainty models were evaluated:

1. reference dosimetry using the PSL-provided electrometer calibration coefficient (k_{elec});
2. reference dosimetry using the user-derived coefficient ($k_{elec,user}$).

The user-dependent uncertainty components were 0.17% and 0.23% (k = 1), respectively. Thus, replacing k_{elec} with $k_{elec,user}$ increased the uncertainty by approximately 0.06 percentage points.

When all uncertainty components were combined, including $N_{D,w}$ and k_Q, the combined standard uncertainty of absorbed dose-to-water determination was 1.6% for both models. The corresponding expanded uncertainty (coverage factor $k = 2$) was 3.2%.

4 DISCUSSION

The purpose of this study was to evaluate the influence of replacing the PSL-provided electrometer calibration coefficient (k_{elec}) with a common user-derived coefficient ($k_{elec,user}$) proposed by Tsuno et al.[9] and to determine the resulting contribution to the uncertainty of absorbed dose-to-water measurements.

As shown in Figures 1 and 2, only small differences were observed between DMU_{elec} and $DMU_{elec,user}$. The mean values and coefficients of variation were nearly identical for both beam qualities investigated. Furthermore, all calculated values remained within ±1.5%, indicating that substitution of k_{elec} with $k_{elec,user}$ produced only minor changes in the calculated absorbed dose-to-water values under the conditions examined in this study.

Tsuno et al.[9] reported that electrometers of the same model exhibited only small variations in sensitivity when evaluated using the SCG002 current source and suggested that a common user-derived coefficient may be applicable within a given electrometer type. The present study extends those findings by evaluating the dosimetric consequences of such coefficient substitution. Although the coefficients themselves differ conceptually from PSL-provided calibration coefficients, the resulting differences in absorbed dose-to-water determination were minimal across multiple institutions using different combinations of linear accelerators and electrometers. These findings support the practical robustness of the approach within the range of systems investigated.

The uncertainty analysis further demonstrated that the influence of $k_{elec,user}$ on the overall uncertainty budget was limited. The user-dependent uncertainty increased from 0.17% to 0.23% ($k = 1$) when $k_{elec,user}$ was used, corresponding to an increase of approximately 0.06 percentage points. However, this contribution remained substantially smaller than the dominant uncertainty sources in reference dosimetry, particularly the beam quality conversion coefficient k_Q, which has been reported to contribute approximately 1.5% uncertainty.[15]

An important observation is that the additional uncertainty associated with $k_{elec,user}$ became negligible when combined with the larger uncertainty components using the root-sum-of-squares (RSS) method recommended by the GUM. As a result, the combined standard uncertainty and expanded uncertainty of absorbed dose-to-water determination remained unchanged at 1.6% and 3.2%, respectively. This finding indicates that small deviations of $k_{elec,user}$ from unity are effectively encompassed within the overall uncertainty budget of reference dosimetry and do not materially influence the final uncertainty estimate.

From a practical perspective, the present results provide quantitative support for the concept proposed by Tsuno et al.[9] that electrometers of the same model may share a common sensitivity coefficient close to unity. The present study does not demonstrate that $k_{elec,user}$ can replace a traceable PSL calibration coefficient. However, the results suggest that modest deviations around $k_{elec,user} \approx 1.000$ contribute only minimally to absorbed dose-to-water uncertainty. Consequently, the use of a common user-derived coefficient may be useful for sensitivity verification and quality-control applications, particularly when evaluating consistency among electrometers of the same model.

A notable strength of this study is the multicenter design. Although the uncertainty propagation equations themselves are independent of institution, measurements were collected from 12 facilities using different combinations of linear accelerators and electrometers. The observed consistency of the results across these systems suggests that the influence of coefficient substitution is not limited to a single institution or dosimetry configuration. This supports the general applicability of the findings within the range of equipment investigated.

The present study does not establish a traceable in-situ calibration methodology, and all electrometers included in the analysis possessed valid calibration coefficients issued by a primary standards laboratory (PSL). It is important to distinguish between traceable calibration and sensitivity verification, as these procedures serve different purposes. Calibration provides metrological traceability and establishes the absolute accuracy of the measurement system, whereas routine in-house verification is primarily intended to detect changes in instrument response over time. Previous studies in industrial metrology have increasingly explored in-situ calibration and verification concepts for sensors and measurement systems.[16–18]

From this perspective, the present findings should be interpreted as supporting the potential use of a common user-derived coefficient for sensitivity verification and constancy checks rather than as a replacement for PSL calibration. The small uncertainty contribution associated with $k_{\mathrm{elec,user}}$ suggests that stable current-source-based methods may provide a practical means of monitoring electrometer performance between scheduled calibration intervals.

Consequently, a complementary quality-assurance strategy may be envisioned, in which periodic PSL calibration maintains traceability while more frequent in-house verification is used to detect unexpected changes in electrometer sensitivity. Further studies addressing long-term stability, traceability, and acceptance criteria will be required before any in-situ calibration framework can be considered.

Several limitations should be acknowledged. First, only 6-MV and 10-MV photon beams were evaluated. Second, all measurements were performed using a Farmer-type ionization chamber, and detector-specific effects were not investigated. Third, the uncertainty associated with $k_{elec,user}$ was derived from previously published SCG002 measurements9 rather than from direct calibration measurements performed in the present study. Further studies involving additional beam qualities, detector types, and long-term stability assessments are therefore warranted.

5 CONCLUSIONS

This study evaluated the influence of replacing the PSL-provided electrometer calibration coefficient (k_{elec}) with a common user-derived coefficient ($k_{elec,user}$) previously proposed for electrometers of the same model. Across 12 institutions and 24 combinations of linear accelerators, ionization chambers, and electrometers, only small differences were observed between (DMU_{elec}) and ($DMU_{elec,user}$).

The uncertainty analysis demonstrated that the use of $k_{elec,user}$ increased the user-dependent uncertainty by approximately 0.06 percentage points. However, this contribution remained substantially smaller than the dominant uncertainty components in reference dosimetry. When combined using the root-sum-of-squares (RSS) method, the resulting combined standard uncertainty and expanded uncertainty of absorbed dose-to-water determination remained unchanged.

These findings indicate that small deviations of $k_{elec,user}$ from unity are effectively encompassed within the overall uncertainty budget of absorbed dose-to-water measurements. The results therefore support the use of a common user-derived coefficient as a practical tool for electrometer sensitivity verification and quality control within a given electrometer type.

Although the present study does not establish a traceable in-situ calibration methodology or replace periodic calibration by a primary standards laboratory, the small uncertainty contribution associated with $k_{elec,user}$ suggests that further investigation of current-source-based sensitivity verification and potential in-situ calibration concepts may be warranted.

Acknowledgement

The authors would like to thank Enago (www. Enago.jp) for the English language review.

Conflict of Interest

The authors declare no conflict of interest.

Funding

None

APPENDIX A

Detailed uncertainty propagation analysis

The uncertainty evaluation was performed according to the Guide to the Expression of Uncertainty in Measurement (GUM). Type A and Type B uncertainty components were combined using the root-sum-of-squares (RSS) method.

A.1 Uncertainty of the temperature-pressure correction factor

The temperature-pressure correction factor was calculated as

$$k_{TP} = \frac{273.2 + T}{273.2 + T_0} \cdot \frac{P_0}{P} \qquad \text{(A1)}$$

where T is the measured water temperature, P is the measured atmospheric pressure, and T_0 and P_0 are the reference temperature and pressure, respectively.

The combined uncertainty of k_{TP} was calculated using

$$u(k_{TP}) = \sqrt{\left(\frac{\partial k_{TP}}{\partial T} u(T)\right)^2 + \left(\frac{\partial k_{TP}}{\partial P} u(P)\right)^2} \qquad \text{(A2)}$$

The sensitivity coefficients were

$$\frac{\partial k_{TP}}{\partial T} = \frac{1}{273.2 + T_0} \cdot \frac{P_0}{P} \qquad \text{(A3)}$$

and

$$\frac{\partial k_{TP}}{\partial P} = -\frac{273.2 + T}{273.2 + T_0} \cdot \frac{P_0}{P^2} \qquad \text{(A4)}$$

respectively.

The uncertainty associated with temperature measurements was calculated as

$$u(T) = \sqrt{u_A(T)^2 + u_{res}(T)^2 + u_{acc}(T)^2} \qquad \text{(A5)}$$

where

$$u_A(T) = \frac{s_T}{\sqrt{n}} \qquad \text{(A6)}$$

is the Type A uncertainty obtained from repeated measurements,

$$u_{res}(T) = \frac{\Delta T/2}{\sqrt{3}} \qquad \text{(A7)}$$

is the uncertainty due to display resolution, and

$$u_{acc}(T) = \frac{a_T}{\sqrt{3}} \qquad \text{(A8)}$$

is the uncertainty associated with instrument accuracy.

Similarly,

$$u(P) = \sqrt{u_A(P)^2 + u_{res}(P)^2 + u_{acc}(P)^2} \qquad \text{(A9)}$$

where

$$u_A(P) = \frac{s_P}{\sqrt{n}} \qquad \text{(A10)}$$

$$u_{res}(P) = \frac{\Delta P/2}{\sqrt{3}} \qquad \text{(A11)}$$

$$u_{acc}(P) = \frac{a_P}{\sqrt{3}} \qquad \text{(A12)}$$

A.2 Uncertainty of the polarity correction factor

The polarity correction factor was calculated as

$$k_{pol} = \frac{|M_+| + |M_-|}{2M_{ref}} \qquad \text{(A13)}$$

where M_+ and M_- are the charge measurements obtained using positive and negative polarities, respectively.

The combined uncertainty was obtained using

$$u(k_{pol}) = \sqrt{\left(\frac{\partial k_{pol}}{\partial M_+} u(M_+)\right)^2 + \left(\frac{\partial k_{pol}}{\partial M_-} u(M_-)\right)^2} \qquad \text{(A14)}$$

The standard uncertainties of the charge measurements were calculated as

$$u(M_+) = \frac{s_+}{\sqrt{n}} \qquad \text{(A15)}$$

and

$$u(M_-) = \frac{s_-}{\sqrt{n}} \qquad \text{(A16)}$$

where s_+ and s_- are the standard deviations of repeated measurements.

A.3 Uncertainty of the ion recombination correction factor

The ion recombination correction factor was determined using measurements acquired at high and low bias voltages.

$$k_s = f(M_H, M_L) \qquad \text{(A17)}$$

where $M_H$and $M_L$denote the charge measurements obtained at high and low voltages, respectively. The uncertainty was calculated according to

$$u(k_s) = \sqrt{\left(\frac{\partial k_s}{\partial M_H} u(M_H)\right)^2 + \left(\frac{\partial k_s}{\partial M_L} u(M_L)\right)^2} \qquad \text{(A18)}$$

with

$$u(M_H) = \frac{s_H}{\sqrt{n}} \qquad \text{(A19)}$$

and

$$u(M_L) = \frac{s_L}{\sqrt{n}} \qquad \text{(A20)}$$

A.4 Uncertainty of the corrected reading

The corrected electrometer reading was calculated as

$$M = M_{raw} k_{TP} k_s k_{pol} k_{elec} \qquad \text{(A21)}$$

The relative standard uncertainty was

$$u_r(M) = \sqrt{u_r(M_{raw})^2 + u_r(k_{TP})^2 + u_r(k_s)^2 + u_r(k_{pol})^2 + u_r(k_{elec})^2} \qquad \text{(A22)}$$

For the user-derived model, $u_r(k_{elec})$was replaced by the variability associated with $k_{elec,user}$reported by Tsuno et al.9.

A.5 Uncertainty of absorbed dose to water

The absorbed dose to water was calculated as

$$D_w = M N_{D,w} k_Q \qquad \text{(A23)}$$

The combined relative standard uncertainty was obtained using

$$u_r(D_w) = \sqrt{u_r(M)^2 + u_r(N_{D,w})^2 + u_r(k_Q)^2} \qquad \text{(A24)}$$

Finally, the expanded uncertainty was calculated as

$$U = k\, u_r(D_w) \qquad \text{(A25)}$$

where $k = 2$ was adopted as the coverage factor.

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Figure legends

FIGURE 1

Box plots of DMU measured using k_{elec} and $DMU_{elec,user}$ measured using $k_{elec,user}$ in 6 MV X-ray. k_{elec} was calibrated by PSL, and $k_{elec,user}$ is the coefficient calculated by sensitivity comparison.

FIGURE 2

Box plots of DMU measured using k_{elec} and $DMU_{elec,user}$ measured using $k_{elec,user}$ in 10 MV X-ray. k_{elec} was calibrated by PSL, and $k_{elec,user}$ is the coefficient calculated by sensitivity comparison.

Table legends

TABLE 1

Summary of uncertainty evaluation methods and propagation equations used for absorbed dose-to-water determination. Detailed derivations are provided in Appendix A. RSS, root-sum-of-squares.

TABLE 2

Uncertainties resulting from calculation of every coefficient.

TABLE 3

Uncertainties resulting from calculation of absorbed dose to water.

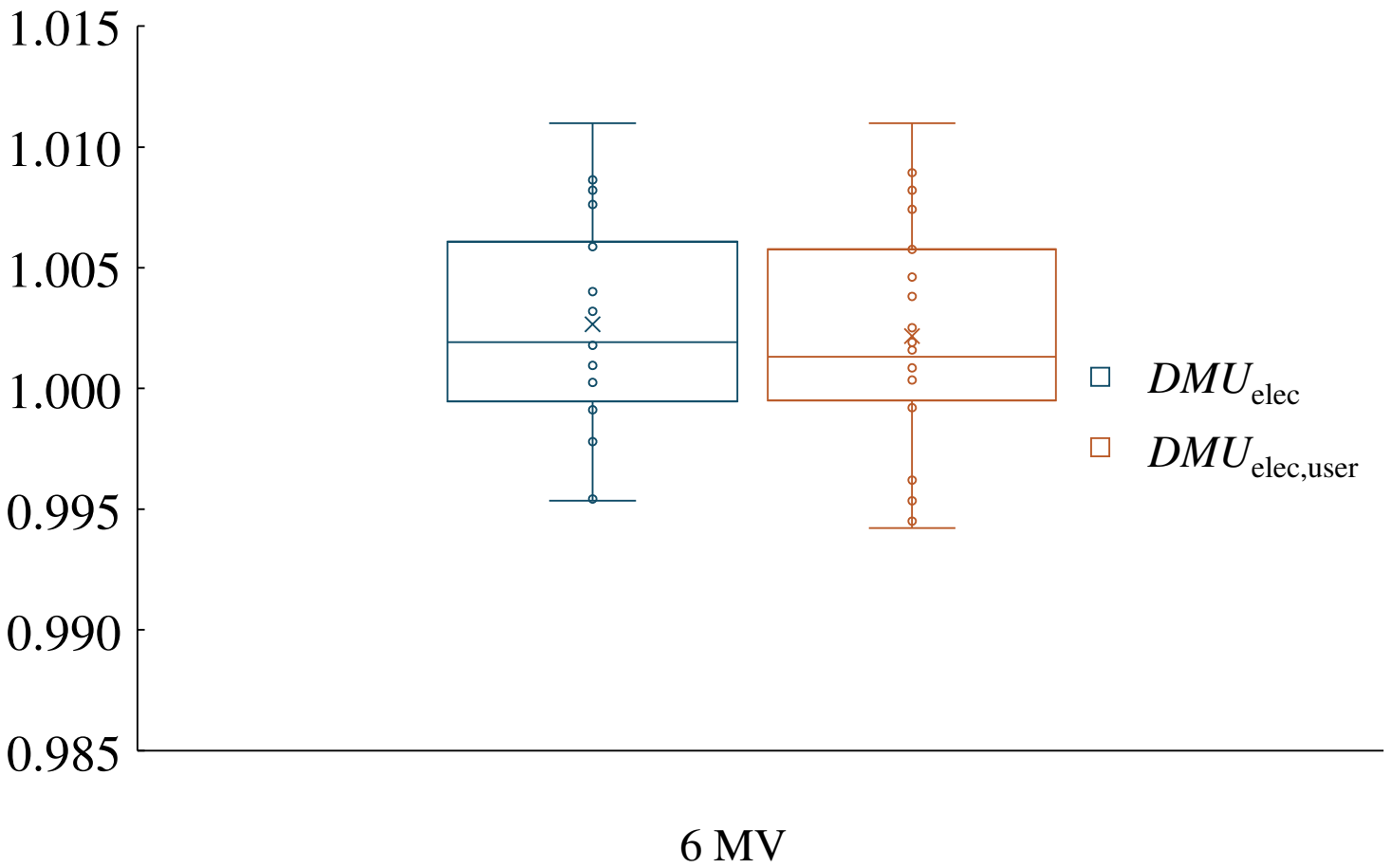


Figure 1

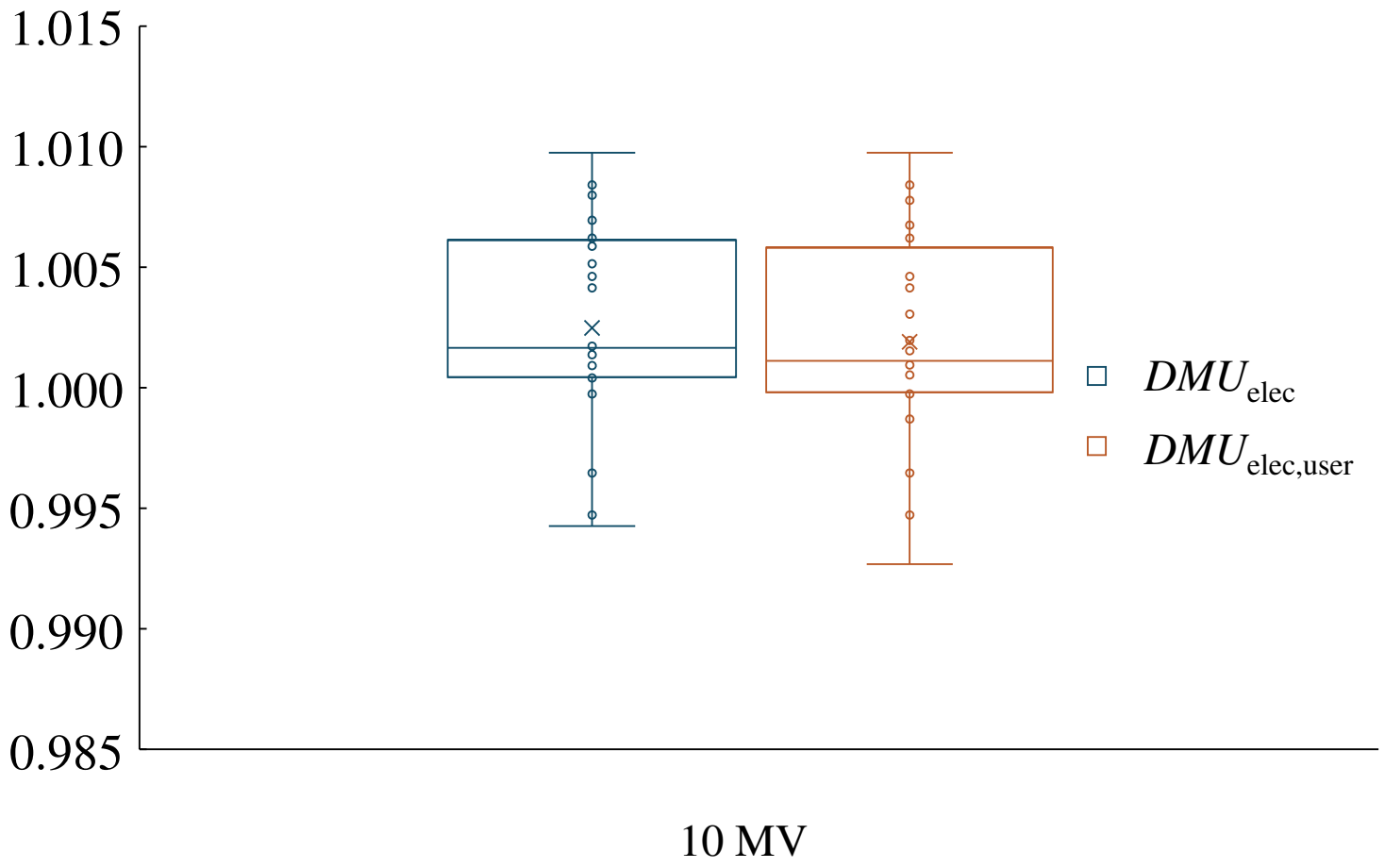

1.015
1.010
1.005
1.000
0.995
0.990
0.985
DMU_{elec}
$DMU_{elec,user}$
10 MV

Figure 2

Quantity	Uncertainty evaluation	Equation
k_{TP}	Type A + Type B	Eq. (A1)–(A12)
k_{pol}	Type A	Eq. (A13)–(A16)
k_s	Type A	Eq. (A17)–(A20)
M	RSS	Eq. (A21)–(A22)
D_w	RSS	Eq. (A23)–(A24)
Expanded uncertainty	Coverage factor ($k = 2$)	Eq. (A25)

Root-sum-of-squares (RSS)

Table 1

Coefficient	Variable	Process	Representative value	Unit	Sample size	Type	Divisor	Differential coefficient	Relative uncertainty [%]
k_{TP}	temperature	σ_T	0.071	Celsius	2	A	$\sqrt{2}$	0.34	0.017
		$m_{displayT}$	0.1	Celsius	-	B	$\sqrt{3}$	0.34	0.010
		$m_{specificationT}$	0.1	Celsius	-	B	$\sqrt{3}$	0.34	0.020
		$uk_{TP}(T)$							0.028
	pressure	σ_P	0.014	kPa	2	A	$\sqrt{2}$	-1.0	-0.010
		$m_{displayP}$	0.001	kPa	-	B	$\sqrt{3}$	-1.0	-0.001
		$m_{specificationP}$	0.015	kPa	-	B	$\sqrt{3}$	-1.0	-0.009
		$uk_{TP}(P)$							0.013
		uk_{TP}	Equation12						0.031
k_{pol}	positive	$CV_{poisitive}$	0.085	%	3	A	$\sqrt{3}$	1	0.049
	negative	$CV_{negative}$	0.077	%	3	A	$\sqrt{3}$	1	0.044
		uk_{pol}	Equation15						0.073
k_s	High	CV_{High}	0.091	%	3	A	$\sqrt{3}$	1	0.053
	Low	CV_{Low}	0.084	%	3	A	$\sqrt{3}$	1	0.048
		uk_s	Equation 18						0.11
$k_{elec,user}$		$uk_{elec,user}$	Tsuno et al. [9]						0.20

Table 1

Process	PSL with k_{elec}	This Study with $k_{elec,user}$
	Uncetainty of measrement	
uM_{raw} (Eq. 19)	0.071	0.0039
uk_{TP} (Eq. 12)	0.031	0.031
uk_{pol} (Eq. 15)	0.073	0.073
uk_{s} (Eq. 18)	0.11	0.11
uk_{elec}	0.080	-
$uk_{elec,user}$ (Ref. 9)	-	0.20
$u_{measurement}$ (Eq. 20)	0.17	0.23
	Uncertainty of PSL	
$N_{D,w}$	0.55	0.55
k_{Q}	1.5	1.5
$uD_{w}(d_{ref})$	1.6	1.6
$UD_{w}(d_{ref})$ $(k = 2)$	3.2	3.2

Table 2