

Review Article

Optimization of a Dosimetric Quality Assurance System for a Medical Linear Accelerator under ISO/IEC 17025 Accreditation: Measurement Stability Assessed by Uncertainty Analysis

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Abstract

Background: Accurate dosimetry is essential for safe and effective radiotherapy. Although international guidelines are available, routine clinical practice does not always include a comprehensive evaluation of measurement uncertainty and methodological stability.

Purpose: This study presents a structured quality assurance system for medical linear accelerators, with particular emphasis on measurement uncertainty analysis as a tool for assessing the stability and robustness of dosimetric procedures.

Materials and Methods: The study was conducted on a fleet of 10 Varian linear accelerators operating in photon and electron energy ranges. Quality control procedures were developed in accordance with international recommendations (IAEA, AAPM, ESTRO) and implemented within an accredited system compliant with PN-EN ISO/IEC 17025. Measurement uncertainty was evaluated using Type A and Type B approaches, including repeatability, reproducibility, and long-term stability analyses.

Results: The implemented framework enabled quantitative evaluation of measurement uncertainty and confirmed compliance with acceptance criteria for all analyzed parameters. Reduced measurement variability and improved repeatability were observed across all monitored procedures.

Conclusions: The implementation of an accredited dosimetric quality assurance system significantly improved measurement consistency and clinical safety. Measurement uncertainty analysis proved to be an effective tool for monitoring stability and minimizing the risk of dosimetric errors in radiotherapy.

Keywords: measurement uncertainty, ISO/IEC 17025 accreditation, radiotherapy dosimetry QA

Introduction

A fundamental prerequisite for safe radiotherapy is the correct and reliable preparation of equipment for clinical use^{6,12}. In the metrological practice of medical physics, numerous national and international recommendations, guidelines, and normative documents are applied, enabling the development of a coherent chain of procedures that ensures the appropriate preparation of devices for operation^{4,6,7–9,16,21}.

The responsibilities of a medical physicist authorizing a linear accelerator for clinical operation include the reliable performance of a series of measurements and their evaluation with respect to correct beam formation and delivery, both in terms of energy and geometry. However, in routine practice, this work is usually not subject to external evaluation other than an annual dosimetric audit based on irradiation of thermoluminescent dosimeter (TLD) capsules with a reference

dose in a single geometric setup of the device. Such audits do not assess documentation, data-acquisition procedures, measurement setups, or—critically—the uncertainty budget of the performed measurements^{6,12}.

Therefore, subjecting the institution to an external assessment, such as accreditation of a metrology laboratory, is of particular value.

An important organizational achievement of our team was obtaining accreditation for compliance with PN-EN ISO/IEC 17025:2005 in the field of dosimetric supervision of radiotherapy processes. The accreditation, numbered AB 1468, was subsequently maintained in two consecutive assessments. Its greatest value lay in the implementation of a structured methodology for uncertainty estimation and error analysis across all dosimetric procedures. This approach enabled systematic assessment of measurement stability and supported long-term optimization of the radiotherapy process.

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Authors' contribution: A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article.

Purpose

The aim of this study is to present the core scope of quality control for a medical linear accelerator, together with a description of measurement uncertainty analysis as a measure of the stability and robustness of the implemented measurements, as assessed by an independent audit conducted by the Polish Centre for Accreditation (PCA). In addition, one selected quality control procedure of a linear accelerator is presented, namely dose-rate measurement.

Materials and Methods

The study was conducted at the Lower Silesian Oncology Center in Wrocław, including affiliated centers, using a fleet of 10 Varian linear accelerators.

Quality control tests for medical linear accelerators are developed individually for each type of therapeutic device, based on the manufacturer's recommendations and guidelines, acceptance tests, instructions and technical schematics, applicable national laws and executive regulations, recommendations of national and international organizations and scientific societies (PTFM, ESTRO, EFOMP), and international organizations supervising the use of ionizing radiation (IAEA, AAPM)^{4,6-10}, as well as mandatory dosimetric reports, including IAEA Technical Reports Series No. 398⁴ and AAPM TG-51¹⁰, Protocol for Clinical Reference Dosimetry of High-Energy Photon and Electron Beams.

Measurements of linear accelerator performance, particularly with regard to beam-energy parameters, are performed by medical physicists with specialist qualifications in medical physics^{6,12}. Although general guidelines and documents describing the estimation of measurement uncertainty are available^{16,21}, they do not provide a universal uncertainty budget suitable for all measurement procedures and clinical conditions. Therefore, each institution should adapt these methods to its own quality control procedures, measurement equipment, calibration data, and accreditation requirements.

The proposed procedures include both physical and geometric control of key parameters of therapeutic systems that are critical to the correct implementation of irradiation techniques used at the center.

The frequency of individual tests was determined on the basis of applicable national guidelines and international recommendations for quality assurance in radiotherapy^{2,3,6-9}. The testing schedule also took into account the principle of rational planning of control procedures and practical aspects related to the availability of the controlled devices under clinical conditions.

In addition, procedures for periodic verification of control and measurement equipment were developed to confirm its stability and metrological consistency between successive calibration or verification processes^{16,21}. This procedure enables ongoing monitoring of the accuracy of the measuring equip-

ment and thus ensures the reliability of results obtained within the quality control program.

For this reason, external assessment is essential, as it provides the basis for building a long-term metrological culture and thereby minimizes the probability of undesirable dosimetric events.

Regardless of the type of measurement (quantitative or qualitative), measurement category (absolute or relative), or test type (subjective or objective), the key considerations are measurement accuracy, reliability, and stability, all supported by a formalized uncertainty-analysis procedure¹⁶⁻²¹.

Methodology for determining the stability of all measurement methods subjected to accreditation assessment in terms of metrological uncertainty

The methodology described below concerns the estimation of measurement uncertainty for the quality control procedures included in the accreditation scope. In this study, uncertainty analysis was used as a supporting tool for assessing the stability of these procedures, based on the identification, quantification, and propagation of relevant uncertainty components¹⁶⁻²¹.

The methods were developed to support the quality control of Varian medical linear accelerators used in the hospital and its affiliated centers. In total, the machine fleet comprises 10 linear accelerators subjected to periodic dosimetric and mechanical quality control tests. The devices generate photon beams with nominal accelerating potentials of 6–18 MV and electron beams with nominal energies of 6–20 MeV. The implementation of these tests is supported by the availability of calibrated measurement equipment, including dosimetric instruments with valid external calibration certificates and, where applicable, legal metrological verification certificates^{16,21}.

The list of procedures covered by certification in accordance with ISO/IEC 17025²¹ for control of linear-accelerator parameters, together with the uncertainty-analysis methodology, includes procedures 1–15:

1. **Beam geometry and laser alignment system**
2. **Absorbed dose rate in a water phantom**
3. **Reference measurement (P0) for a Plexiglas phantom**
4. **Reference measurement (PDM) for the dose monitor**
5. **Flatness and symmetry of beam profiles**
6. **Percentage depth dose (PDD) for radiation beams**
7. **Tissue-phantom ratio energy factor (TPR) for photon beams**
8. **R50 parameter for electron beams**
9. **Physical wedge factors**
10. **Transmission factors through Plexiglas plates**
11. **Transmission factor through a Wood's alloy block**
12. **Long- and short-term stability of accelerator performance**
13. **Stability of accelerator performance as a function of the number of monitor units (MU), proportionality**
14. **Absorbed dose rate in a Plexiglas phantom**
15. **Stability of indications and intrinsic drift of the therapeutic dosimeter**

The preparatory process for accreditation lasted approximately 12 months and included four main stages.

Stage 1 – Initial State Analysis (3 months)

The first stage involved reviewing existing measurement procedures, identifying gaps relative to the standard requirements, performing risk analysis in clinical dosimetry, and evaluating the status of technical and metrological documentation. During this period, an implementation schedule and a process map of the Department were developed, enabling systematic planning of subsequent activities.

Stage 2 – Development of the Documentation System (8 months)

The second stage, which was the most labor-intensive, involved the development of comprehensive system documentation carried out simultaneously in two areas:

Management Documentation – compliant with accreditation requirements, including the Quality Manual, Quality Policy, system procedures covering document and record control, handling of nonconformities, internal audits, management reviews, and the risk management procedure.

Technical Documentation – detailed measurement instructions for each method, uncertainty budget sheets, templates for measurement reports, environmental condition recording forms, equipment logbooks, and schedules for calibrations and technical inspections. In total, more than 80 documented procedures and instructions were developed and approved.

Stage 3 – Technical Preparation for Accreditation

Simultaneously with the documentation development, technical preparations were conducted, including establishment of the uncertainty budget for all measurement methods^{16–18,20}. This process involved identifying all uncertainty components, converting them to a common relative form, and creating spreadsheets that allowed ongoing updates of the budgets when input parameters changed (e.g., after equipment recalibration). The uncertainty assessment included Type A analysis (statistical, based on repeated measurements), Type B analysis (based on calibration certificates, manufacturer tolerances, literature data, and expert judgment), and determination of expanded uncertainty using a coverage factor of $k = 2$ ¹⁶.

At the same time, validation of the measurement methods was conducted. This included repeatability studies (10–20 measurement series per method), reproducibility analysis involving different operators, assessment of long-term stability of measurement systems, tests of resistance to temperature and pressure changes, and drift analysis of ionization chambers. The validation measurements made it possible to define key quality indicators, acceptance limits, compliance criteria, and procedures to be followed when established permissible values were exceeded.

A complete metrological traceability chain was implemented, including calibration of ionization chambers in accredited laboratories, systematic trend analysis based on calibration certificates, and a 12-month advance calibration schedule.

Each measurement device was assigned an individual identifier and a complete set of information regarding calibration status, maintenance and inspection history, and assessment of the impact of any nonconformity on the reliability of measurement results^{16,21}.

Stage 4 – Accreditation Audit

The audit included document review, observation of measurement procedures, verification of uncertainty budgets, assessment of measurement traceability, and personnel interviews. The most important outcome of the closing meeting was confirmation that no significant technical nonconformities had been identified, accompanied by a positive evaluation of the uncertainty budgets and acknowledgment of the clarity of the documentation.

Determination of the Stability of Measurement Methods with Respect to the Definition of Measurement Uncertainty

It is well established that any measurement result represents only an approximation of the true value of the measured quantity^{16,17,18,21}. Many components may contribute to this limited precision. Most commonly, these include observer-related inaccuracies (e.g., during instrument reading), imperfections of measurement methods, limitations of metrological equipment, variability in environmental conditions (e.g., temperature and humidity), as well as approximations of physical constants and rounding of results^{13–21}. Therefore, it is necessary to determine the degree of approximation to the true value and to report it together with the result^{16,21}. Only then do measurement results convey information about measurement quality and allow meaningful comparison^{16–18}.

Concept of Measurement Error

Regardless of the measurement method, it is never possible to determine the true value of a physical quantity with absolute accuracy^{13–18,21}. The difference between the measurement result and the true value of the measured quantity is referred to as the measurement error^{21–23}. Measurement errors are traditionally classified as gross errors (blunders), random errors, and systematic errors^{13,14,17,18,20,23}.

Gross errors usually arise from inattention or carelessness of the observer when reading or recording results, or as a consequence of sudden changes in measurement conditions. If a series of measurements is available, results affected by gross errors are relatively easy to identify and eliminate.

Systematic errors result from imperfections of instruments and measurement methods. They can be reduced by using more advanced and precise methods and instruments; however, complete elimination of systematic errors is not possible. Identified systematic errors should be taken into account by introducing appropriate corrections to the result. A typical example is the correction for the internal resistance of a voltmeter when measuring voltage.

Random errors are always present. They arise from various random and uncontrollable factors (e.g., temperature fluctuations or air movement in the vicinity of the measuring instrument). Another cause may be a mismatch between the adopted model and the measured object. The existence of random errors is evidenced by the lack of repeatability of measurement results of the same quantity. Random errors can be reduced by repeating measurements multiple times, which leads to partial compensation of randomly positive and negative deviations of the result.

Concept of Measurement Uncertainty

Since the true value of the measured quantity is never known, the practical usefulness of the concept of measurement error is limited^{16,21}. At present, evaluation of measurement results should follow the recommendations of the Guide to the Expression of Uncertainty in Measurement (International Organization for Standardization, Geneva, 1995)¹⁶. This standard, agreed in 1995 and adopted into Polish practice in 1999, is applicable across a wide range of scientific and technical fields.

The international standard recommends the use of the term measurement uncertainty, defined as a parameter characterizing doubt about the value of a measurement result^{16,21}. Standard uncertainty may be estimated in two ways:

Type A, based on statistical analysis of a series of measurements; and

Type B, based on the scientific judgment of the observer^{16-18,20}.

The symbol for standard uncertainty is u (from “uncertainty”), which may be written in different forms, e.g., u or $u(x)$. The advantage of this notation is that the measured quantity can be expressed verbally, which facilitates the preparation of measurement documentation¹⁶. It should be remembered, however, that u is not a function but a numerical value.

Standard Uncertainty of Direct Measurements

Assume that a series of n direct measurements of a physical quantity X has been performed, yielding the results^{16-18,20}. If the measurement results are not identical, the value closest to the true value is assumed to be the arithmetic mean of all measurement results¹⁶⁻¹⁸:

$$X \approx \bar{X} = \frac{1}{n} \sum_{i=1}^n X_i \quad (1)$$

This statement becomes increasingly valid as the number of measurements increases. In order to determine the standard uncertainty in this case, the Type A method is applied, i.e., the standard deviation of the mean is calculated as^{16-18,20}:

$$u(X) = \sqrt{s_{\bar{X}}} = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n \cdot (n-1)}} \quad (2)$$

If the measurement results show no observable dispersion, or if only a single measurement result is available, the standard uncertainty may be estimated using a Type B evaluation^{16-18,20}. In such cases, information provided by the instrument manu-

facturer, such as the maximum permissible error, accuracy specification, or tolerance limit, may be used. If no additional information on the probability distribution is available, a rectangular distribution may be assumed and the standard uncertainty can be calculated as:

$$u(X) = \frac{\Delta X}{\sqrt{3}} \quad (3)$$

However, the choice of distribution should be justified on the basis of the available information. If values close to the center of the interval are more likely than values close to its limits, a triangular distribution may be applied instead.

For simple instruments (e.g., a ruler, micrometer screw gauge, or thermometer), may be taken as the instrument resolution (scale division). In digital electronic instruments, the maximum uncertainty is provided by the manufacturer in the operating manual and is usually several times greater than the least significant digit^{17,18,20}.

Most often, it depends on the measured value X and the measurement range Z :

If both types of uncertainty occur (i.e., both the dispersion of results and calibration uncertainty) and neither can be neglected (i.e., both are of the same order of magnitude), the total standard uncertainty is calculated as^{16-18,20}:

$$u(X) = \sqrt{s_{\bar{X}}^2 + \frac{(\Delta X)^2}{3}} \quad (4)$$

Standard Uncertainty of Indirect Measurements: Combined Uncertainty

In the case of indirect measurements, the measured quantity Y is calculated using a functional relationship, which can be written in the general form, where x_i denote k physical quantities measured directly^{16-18,20}. It is assumed that the measurement results and their standard uncertainties are known. The final measurement result is then given accordingly. For uncorrelated indirect measurements (i.e., when each of the quantities x_i is measured independently), the combined standard uncertainty of Y is estimated using the approximate propagation formula:

$$u_c(Y) = \sqrt{\sum_{j=1}^k \left[\frac{\partial f}{\partial X_j} (\bar{X}_1, \bar{X}_2, \dots, \bar{X}_k) \right]^2 \cdot u^2(\bar{X}_j)} \quad (5)$$

Expanded Uncertainty

Standard uncertainty characterizes the dispersion of values that could reasonably be attributed to the measurand and is expressed as a standard deviation. It should not be interpreted as a complete and unambiguous characterization of the measurement result. For practical applications, including the assessment of agreement with reference values, tolerance limits, or other measurement results, the expanded uncertainty is commonly reported. It is denoted as U , or as U_c when obtained from a combined standard uncertainty, and is calculated as:

$$U(X) = k u(X) \quad \text{or} \quad U_c(X) = k u_c(X) \quad (6)$$

The coverage factor k is selected on the basis of the assumed probability distribution, the effective number of degrees of freedom, and the required level of coverage. For a normal distribution and a sufficiently large effective number of degrees of freedom, $k=2$ is commonly used to obtain an expanded uncertainty corresponding approximately to a 95% level of coverage. In other cases, the coverage factor should be selected according to the appropriate probability distribution and the required confidence level¹⁶⁻¹⁸.

Total Differential Method

The estimation of measurement uncertainty using the total differential method may be applied to measurements of uncorrelated quantities. Let x_i be the estimates of the directly measured quantities, and $u(x_i)$ their associated standard uncertainties. If a functional relationship exists: then the uncertainty of Y is determined according to:

$$u_{tz}(Y) = \sum_{j=1}^k \left| \frac{\partial f}{\partial X_j}(\overline{X_1}, \overline{X_2}, \dots, \overline{X_k}) \right| \cdot u(\overline{X_j}) \quad (7)$$

When estimating uncertainties using the total differential method, attention must be paid to the relationship between the combined standard uncertainty and the uncertainty obtained from the total differential method.

$$\begin{aligned} \sqrt{\sum_{j=1}^k \left[\frac{\partial f}{\partial X_j}(\overline{X_1}, \overline{X_2}, \dots, \overline{X_k}) \right]^2 \cdot u^2(\overline{X_j})} &\leq \\ &\leq \sum_{j=1}^k \left| \frac{\partial f}{\partial X_j}(\overline{X_1}, \overline{X_2}, \dots, \overline{X_k}) \right| \cdot u(\overline{X_j}) \end{aligned} \quad (8)$$

and the uncertainty obtained from the total differential method

$$u_c(Y) \leq u_{tz}(Y)$$

This means that the total differential method may be used to estimate the uncertainty of combined quantities of uncorrelated variables; however, one must be aware that the resulting uncertainty may be overestimated^{17,18,20}.

Standard Uncertainty of Correlated Quantities

When calculating standard uncertainty, it is necessary to distinguish between uncorrelated and correlated measurements of directly measured quantities^{17,18,20,21}. This concept can be illustrated using two quantities, X and Z . Let x_i and z_i be the results of a series of measurements of X and Z .

The sample correlation coefficient is defined as:

$$r_{X,Z} = \frac{\sum_{i=1}^n (x_i - \bar{x})(z_i - \bar{z})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \cdot \sqrt{\sum_{i=1}^n (z_i - \bar{z})^2}} = \frac{s_{X,Z}}{s_X \cdot s_Z} \quad (9)$$

where
$$s_{X,Z} = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})(z_i - \bar{z})$$

The correlation coefficient takes values in the interval $[-1, 1]$. If the points lie on a straight line, the quantities X and Z are fully correlated. If $r = 0$, the quantities are uncorrelated^{17,18}.

Furthermore, the measurements of physical quantities should be considered correlated when they are repeatedly measured using the same experimental setup^{17,18,20}. In such cases, correlations between individual directly measured quantities must be taken into account, and the combined standard uncertainty of the indirectly measured quantity Y is expressed as:

$$u_s(Y) = \sqrt{\sum_{j=1}^k \left[\frac{\partial Y}{\partial X_j} \right]^2 u^2(\overline{X_j}) + 2 \sum_{j=1}^k \sum_{i=j+1}^k \left(\frac{\partial Y}{\partial X_j} \right) \left(\frac{\partial Y}{\partial X_i} \right) u(\overline{X_j}) u(\overline{X_i}) \cdot r_{X_j, X_i}} \quad (10)$$

For correlated quantities, the total differential method should not be used, because the uncertainty value determined using Equation 16 may be smaller or larger than the standard uncertainty of indirect measurements determined using Equation 6.

Below, all methodologies for uncertainty calculations applied to procedures 1–15 are presented. Formula numbers have been introduced here in a single continuous sequence to improve readability and consistency across the manuscript.

1. Radiation Beam Geometry and Laser Alignment System

Internal process identification No. P-XI/INd-06

1.1. Verification of telemeter linearity

The estimated Type B uncertainty is based on the observer's expert judgment, according to Equation 3, where ΔX denotes the smallest scale division of the telemeter.

1.2. Verification of the isocenter

The estimated Type B uncertainty is based on the observer's expert judgment, according to Equation 3, where ΔX denotes the smallest scale division of the telemeter.

1.3. Verification of centering indicators

The estimated Type B uncertainty is based on the observer's expert judgment, according to Equation 3, where ΔX denotes the line width of the centering indicator.

1.4. Verification of agreement between the light field and the reference field template

The estimated Type B uncertainty is based on the observer's expert judgment, according to Equation 3, where ΔX denotes the unit scale division of the field template.

1.5. Verification of agreement between the radiation field and the light field on radiographic film

The estimated Type B uncertainty is based on the observer's expert judgment, according to Equation 3, where ΔX denotes the smallest scale division of the ruler.

1.6. Verification of agreement of four asymmetric radiation fields on radiographic film

The estimated Type B uncertainty is based on the observer's expert judgment, according to Equation 3, where ΔX denotes the smallest scale division of the ruler.

2. Absorbed Dose Rate in a Water Phantom

Internal process identification No. P-XI/IND-084

Formula for determining the dose rate:

$$D_{w(Z,ref)} = \frac{\bar{M}}{300} \cdot N_{D,w,Q} \cdot k_{p,T} \cdot k_{pol} \cdot k_s \cdot k_{Q,Q_0} \cdot k_{PDD} \quad (11)$$

The proposed formula is based on the formalism recommended in the IAEA TRS-398 report, where the absorbed dose to water in a beam of quality Q is determined from the corrected dosimeter reading M_Q , the calibration coefficient N_{D,w,Q_0} and the beam-quality correction factor k_{Q,Q_0} . In the present study, the corrected dosimeter reading M_Q was explicitly expressed as the mean dosimeter reading normalized to the number of monitor units and multiplied by the relevant correction factors, namely the temperature–pressure correction factor $k_{p,T}$, the polarity correction factor k_{pol} , and the ion recombination correction factor k_s . Thus, the formula used in this work is a direct expansion of the TRS-398 notation adapted to the measurement procedure applied in the study.

Standard uncertainty of the absorbed dose rate in the water phantom (according to Equation 5):

$$\begin{aligned} u_c(D_{w(Z,ref)}) = & \\ & = \frac{1}{300} \sqrt{(N_{D,w,Q} \cdot k_{p,T} \cdot k_{pol} \cdot k_s \cdot k_{Q,Q_0} \cdot k_{PDD})^2 \cdot u(\bar{M})^2} \\ & + \frac{1}{300} \sqrt{(\bar{M} \cdot k_{p,T} \cdot k_{pol} \cdot k_s \cdot k_{Q,Q_0} \cdot k_{PDD})^2 \cdot u(N_{D,w,Q})^2} \\ & + \frac{1}{300} \sqrt{(\bar{M} \cdot N_{D,w,Q} \cdot k_{pol} \cdot k_s \cdot k_{Q,Q_0} \cdot k_{PDD})^2 \cdot u(k_{p,T})^2} \\ & + \frac{1}{300} \sqrt{(\bar{M} \cdot N_{D,w,Q} \cdot k_{p,T} \cdot k_s \cdot k_{Q,Q_0} \cdot k_{PDD})^2 \cdot u(k_{pol})^2} \\ & + \frac{1}{300} \sqrt{(\bar{M} \cdot N_{D,w,Q} \cdot k_{p,T} \cdot k_{pol} \cdot k_{Q,Q_0} \cdot k_{PDD})^2 \cdot u(k_s)^2} \\ & + \frac{1}{300} \sqrt{(\bar{M} \cdot N_{D,w,Q} \cdot k_{p,T} \cdot k_s \cdot k_{Q,Q_0} \cdot k_{PDD})^2 \cdot u(k_{pol})^2} \\ & + \frac{1}{300} \sqrt{(\bar{M} \cdot N_{D,w,Q} \cdot k_{p,T} \cdot k_s \cdot k_{pol} \cdot k_{PDD})^2 \cdot u(k_{Q,Q_0})^2} \\ & + \frac{1}{300} \sqrt{(\bar{M} \cdot N_{D,w,Q} \cdot k_{p,T} \cdot k_s \cdot k_{pol} \cdot k_{Q,Q_0})^2 \cdot u(k_{PDD})^2} \end{aligned} \quad (12)$$

Where (according to Equation 4):

the calibration certificate of the ionization chamber provides the calibration coefficient N_{D,w,Q_0} together with its expanded uncertainty $U(N_{D,w,Q_0})$ and the corresponding coverage factor k . Therefore, the standard uncertainty of the calibration coefficient should be calculated as:

$$u(N_{D,w,Q_0}) = \frac{U(N_{D,w,Q_0})}{k} \quad (13)$$

$$u(\bar{M}) = \sqrt{s_{\bar{X}}^2 + \frac{(\Delta_{max})^2}{3}} = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n \cdot (n-1)} + \frac{(\Delta_{max})^2}{3}} \quad (14)$$

Δ_{max} is the maximum indication error of the electrometer (0.0005 nC).

$$u(k_{p,T}) = \sqrt{\left(\frac{1013}{p \cdot 293.15} \cdot \Delta_{max-T}\right)^2 + \left(\frac{273.15 + T}{293.15} \cdot \frac{1013}{p^2} \cdot \Delta_{max-p}\right)^2} \quad (15)$$

Δ_{max-T} – is the maximum error of temperature measurement (0.05 °C).

Δ_{max-p} – is the maximum error of pressure measurement (1.5 hPa).

$$u(k_{pol}) = \sqrt{\left(\frac{2 \cdot M_+ \cdot s(M_+)}{4(M_{stand})^2}\right)^2 + \left(\frac{2 \cdot (M_+ + M_-) \cdot s(M_-)}{4(M_{stand})^2}\right)^2} \quad (15)$$

$s(M_+)$ – is the standard deviation of the mean for readings M_+ .

$s(M_-)$ – is the standard deviation of the mean for readings M_- .

$$u(k_s) = \sqrt{\left(a_1 \left(\frac{s(M_1) \cdot M_2 + M_1 \cdot s(M_2)}{M_2^2}\right)\right)^2 + \left(2 \cdot a_2 \frac{M_1}{M_2} \left(\frac{s(M_1) \cdot M_2 + M_1 \cdot s(M_2)}{M_2^2}\right)\right)^2} \quad (16)$$

$s(M_1)$ – is the standard deviation of the mean for readings M_1 .

$s(M_2)$ – is the standard deviation of the mean for readings M_2 .

$u(k_{Q,Q_0})$ – is the uncertainty associated with reading the value from Table 14 of the TRS-398 report as a function of the TPR coefficient.

$$u(k_{PDD}) = \frac{PDD \cdot \Delta_{max}}{100\%} \quad (17)$$

Δ_{max} – is the maximum error of determining the PDD value (1.0%).

3. Reference Measurement (P₀) for the PMMA Phantom

Internal process identification No. P-XI/IND-13^{7,8,12}

Auxiliary formula and reference measurement formula:

$$P_{meas.} = \frac{\bar{M}}{300} \cdot k_{p,T} \quad (18)$$

Standard uncertainty of the reference measurement in the PMMA phantom (according to Equation 5):

$$u_c(P_{\text{meas.}}) = \frac{1}{300} \sqrt{(k_{p,T})^2 \cdot s(\bar{M})^2 + (\bar{M})^2 \cdot u(k_{p,T})^2} \quad (19)$$

4. Reference Measurement PDM for the Dose Monitor

Internal process identification No. P-XI/IND-14

Auxiliary formula and reference measurement formula for the dose monitor:

$$P_{\text{DM-meas.}} = \frac{\bar{M}}{300} \cdot k_{p,T} \quad (20)$$

$$P_{\text{DM}} = \frac{D_{w(\text{Z ref})\text{-TPS}}}{D_{w(\text{Z ref})\text{-meas.}}} P_{\text{DM-meas.}} \quad (21)$$

Standard uncertainty of the reference measurement for the dose monitor (according to Equation 5):

$$u_c(P_{\text{DM-meas.}}) = \frac{1}{300} \sqrt{(k_{p,T})^2 \cdot s(\bar{M})^2 + (\bar{M})^2 \cdot u(k_{p,T})^2} \quad (22)$$

5. Flatness and Symmetry of Radiation Beam Profiles

Internal process identification No. P-XI/IND-10^{6,12}

Formulas for flatness (Flat) and symmetry (Sym) of beam profiles:

$$\text{Flat} = 100 \cdot \frac{|D_{\text{max}} - D_{\text{min}}|}{|D_{\text{max}} + D_{\text{min}}|} \quad (23)$$

$$\text{Sym} = 100 \cdot \text{MAX}(|\text{PointL}/\text{PointR}|, |\text{PointR}/\text{PointL}|) \quad (24)$$

Standard uncertainty of flatness and symmetry (according to Equation 5):

$$u_c(\text{Flat}) = 100 \sqrt{\left(\frac{|D_{\text{max}} + D_{\text{min}}| - |D_{\text{max}} - D_{\text{min}}|}{|D_{\text{max}} + D_{\text{min}}|^2} \right)^2 \cdot u(D_{\text{max}})^2 + \left(\frac{|D_{\text{max}} + D_{\text{min}}| - |D_{\text{max}} - D_{\text{min}}|}{|D_{\text{max}} + D_{\text{min}}|^2} \right)^2 \cdot u(D_{\text{min}})^2} \quad (25)$$

$$u_c(\text{Sym}) = 100 \sqrt{\left(\frac{1}{\text{PointR}} \right)^2 \cdot u(\text{PointL})^2 + \left(\frac{\text{PointL}}{(\text{PointR})^2} \right)^2 \cdot u(\text{PointR})^2} \quad (26)$$

where:

$$u(D_{\text{max}}) = u(D_{\text{min}}) = \frac{D \cdot \Delta_{\text{max}}}{100\%} \quad (27)$$

Δ_{max} – is the maximum error of determining D from the PDD curve (1.0%).

$$u(\text{PointR}) = u(\text{PointL}) = \frac{\text{Point} \cdot \Delta_{\text{max}}}{100\%} \quad (28)$$

Δ_{max} – is the maximum error of determining Point from the PDD curve (1.0%).

6. Percentage Depth Dose (PDD) for Radiation Beams

Internal process identification No. P-XI/IND-09^{4,12}

$$u(\text{PDD}) = \frac{\text{PDD} \cdot \Delta_{\text{max}}}{100\%} \quad (29)$$

Δ_{max} – is the maximum error of determining the PDD value (1.0%).

7. Tissue-Phantom Ratio (TPR) for Photon Beams

Internal process identification No. P-XI/IND-11^{4,12}

Formula for determining the energy quality factor TPR:

$$\text{TPR} = 1.2661 \cdot \frac{\text{PDD}_{20}}{\text{PDD}_{10}} - 0.0595 \quad (30)$$

Standard uncertainty of TPR (according to Equation 5):

$$u_c(\text{TPR}) = 1.2661 \sqrt{\left(\frac{1}{\text{PDD}_{10}} \right)^2 \cdot u(\text{PDD}_{20})^2 + \left(\frac{\text{PDD}_{20}}{(\text{PDD}_{10})^2} \right)^2 \cdot u(\text{PDD}_{10})^2} \quad (31)$$

where:

$$u(\text{PDD}) = \frac{\text{PDD} \cdot \Delta_{\text{max}}}{100\%}$$

Δ_{max} – is the maximum error of determining PDD (1.0%).

8. R50,D parameter for electron beam energy

Internal process identification No. P-XI/IND-12^{4,12}

Formula for determining $R_{50,D}$:

$$R_{50,D} = 1.029 \cdot R_{50,\text{ion}} - 0.06 \quad (32)$$

Standard uncertainty of R50,D (according to Equation 5):

$$u_c(R_{50,D}) = 1.029 \sqrt{u(R_{50,D})^2} \quad (33)$$

where:

$$u(R_{50,D}) = \Delta_{\text{max}}$$

Δ_{max} – is the maximum error of determining R50,D (0.2mm).

9. Physical Wedge Factors

Internal process identification No. P-XI/IND-16^{7,8,12}

Formula for the physical wedge factor K_{wedge} :

$$K_{\text{wedge}} = \frac{\bar{M}_{\text{open}}}{\bar{M}_{\text{wedge}}} \quad (34)$$

Standard uncertainty of the physical wedge factor K_{wedge} (according to Equation 5):

$$u_c(K_{\text{wedge}}) = \sqrt{\left(\frac{1}{\bar{M}_{\text{wedge}}} \right)^2 \cdot s(\bar{M}_{\text{open}})^2 + \left(\frac{\bar{M}_{\text{open}}}{(\bar{M}_{\text{wedge}})^2} \right)^2 \cdot s(\bar{M}_{\text{wedge}})^2} \quad (35)$$

where:

$s(\bar{M}_{\text{open}})$ – is the standard deviation of the mean for the open field,

$s(\bar{M}_{\text{wedge}})$ – is the standard deviation of the mean for the wedged field.

10. Transmission Factors of PMMA Plates-tray

Internal process identification No. P-XI/IND-20¹²

Formula for the PMMA plate transmission factor K_{tray} :

$$K_{tray} = \frac{\bar{M}_{tray}}{\bar{M}_{open}} \quad (36)$$

Standard uncertainty of the PMMA plate transmission factor (according to Equation 5):

$$u_c(K_{tray}) = \sqrt{\left(\frac{1}{\bar{M}_{open}}\right)^2 \cdot s(\bar{M}_{tray})^2 + \left(\frac{\bar{M}_{tray}}{(\bar{M}_{open})^2}\right)^2 \cdot s(\bar{M}_{open})^2} \quad (37)$$

where:

$s(M_{open})$ – is the standard deviation of the mean for the open field

$s(M_{tray})$ – is the standard deviation of the mean for the field with PMMA plate.

11. Transmission Factor of a Wood's Alloy Block

Internal process identification No. P-XI/IND-21¹²

Formula for the Wood's alloy block transmission factor K_{block} :

$$K_{block} = \frac{\bar{M}_{block}}{\bar{M}_{open}} \quad (38)$$

Standard uncertainty of the block transmission factor K_{block} (according to Equation 5):

$$u_c(K_{block}) = \sqrt{\left(\frac{1}{\bar{M}_{open}}\right)^2 \cdot s(\bar{M}_{block})^2 + \left(\frac{\bar{M}_{block}}{(\bar{M}_{open})^2}\right)^2 \cdot s(\bar{M}_{open})^2} \quad (39)$$

where:

$s(M_{open})$ – is the standard deviation of the mean for the open field,

$s(M_{block})$ – is the standard deviation of the mean for the field with Wood's alloy block.

12. Long- and Short-Term Stability of Accelerator Operation

Internal process identification No. P-XI/IND-18^{6,12}

Formula for absorbed dose rate measurement required for stability analysis:

$$P_{meas.} = \frac{\bar{M}}{300} \cdot k_{p,T} \quad (40)$$

Standard uncertainty of absorbed dose rate for stability assessment (according to Equation 5):

$$u_c(P_{meas.}) = \frac{1}{300} \sqrt{\left(k_{p,T}\right)^2 \cdot s(\bar{M})^2 + (\bar{M})^2 \cdot u(k_{p,T})^2} \quad (41)$$

Average output over a quarter and the reproducibility coefficient:

$$P = \frac{100}{\bar{W}} \sqrt{\frac{\sum_{i=1}^n (\bar{W} - W_i)^2}{(n-1)}} \quad (42)$$

where:

$\bar{W}$ – average output over the quarter

W_i – individual output measurements

n – number of measurements

13. Accelerator Stability as a Function of MU

Internal process identification No. P-XI/IND-24^{6,12}

Formula for accelerator stability as a function of MU:

$$P_s = \bar{M} \cdot k_{p,T} \quad (43)$$

Standard uncertainty of accelerator stability as a function of MU (according to Equation 5):

$$u_c(P_s) = \sqrt{\left(k_{p,T}\right)^2 \cdot s(\bar{M})^2 + (\bar{M})^2 \cdot u(k_{p,T})^2} \quad (44)$$

where:

$s(M)$ – standard deviation of the mean for MU measurements in the range 50–600

14. Absorbed Dose Rate in Plexiglas Phantom

Internal process identification No. P-XI/IND-04¹²

Formula for absorbed dose rate measurement in a Plexiglas phantom:

$$P_{meas.} = \frac{\bar{M}}{300} \cdot k_{p,T} \quad (45)$$

Standard uncertainty (according to Equation 5):

$$u_c(P_{meas.}) = \frac{1}{300} \sqrt{\left(k_{p,T}\right)^2 \cdot s(\bar{M})^2 + (\bar{M})^2 \cdot u(k_{p,T})^2} \quad (46)$$

15. Stability and Intrinsic Drift of the Therapeutic Dosimeter

Internal process identification No. P-XI/IND-33^{16-18,20,21}

Corrected average reading of the dosimeter in the control source:

$$M_{0T} = \bar{M} \cdot k_{p,T} \cdot 2^{\frac{t_r}{T_{0.5}}} \quad (47)$$

where:

t_r – time interval between current check and reference check in calibration certificate

$T_{0.5}$ – half-life of the control source (Sr-90; $T_{0.5} = 28.7$ years)

Percent deviation M of the measured value relative to the certificate:

$$\sigma M = \left[\frac{M_{0T}}{M_0} - 1 \right] 100\% \quad (48)$$

Standard uncertainty of the corrected dosimeter reading (according to Equation 5):

$$u_c(M_{0T}) = \sqrt{\left(k_{p,T} \cdot 2^{\frac{t_r}{T_{0.5}}}\right)^2 \cdot s(\bar{M})^2 + \left(\bar{M} \cdot 2^{\frac{t_r}{T_{0.5}}}\right)^2 \cdot u(k_{p,T})^2 + (\bar{M} \cdot k_{p,T})^2 \cdot u\left(2^{\frac{t_r}{T_{0.5}}}\right)^2} \quad (49)$$

Standard uncertainty of percent deviation:

$$u_c(\sigma M) = \sqrt{\left(\frac{1}{M_0}\right)^2 \cdot u(M_{0T})^2 + \left(\frac{M_{0T}}{M_0}\right)^2 \cdot u(M_0)^2} \quad (50)$$

Results

Implementation of the uncertainty-based quality assurance framework enabled quantitative assessment of the stability of dosimetric procedures included in the accredited system. The main practical effect of the implemented approach was the transition from a purely tolerance-based evaluation of measurement results to an evaluation that considered both the measured deviation and the uncertainty associated with the measurement method.

For each procedure, measurement results were analyzed using three complementary indicators: the mean deviation from the reference value, the observed measurement variability, and the expanded uncertainty calculated using a coverage factor of $k = 2$. This approach allowed routine measurement scatter to be distinguished from deviations that could indicate a true change in accelerator performance or in the response of the measuring system.

The numerical values in **Table 1** summarize internal validation and routine quality control data collected during the implementation and maintenance of the accredited dosimetric quality assurance system. The values illustrate the practical effect of standardizing measurement conditions, introducing documented uncertainty budgets, and applying consistent criteria for result interpretation.

Example: absorbed dose rate in a water phantom

The most clinically relevant example was the absorbed dose rate measurement in a water phantom, because this procedure is directly linked to reference dosimetry and accelerator output constancy. After implementation of the uncertainty-based procedure, the range of observed deviations decreased from 1.1–1.6% to 0.4–0.7%. The reduction was mainly associated with standardization of environmental corrections, consistent application of the calibration coefficient, repeated verification of electrometer readings, and formalized documentation of measurement conditions.

Table 2 presents a representative comparison of five measurement sessions performed before and after implementation of the uncertainty-based procedure.

Table 2. Example of observed deviation from the reference value for absorbed dose rate measurement in a water phantom.

Measurement session	Deviation from reference before uncertainty-based optimization	Deviation from reference after uncertainty-based optimization
1	1.3%	0.5%
2	1.5%	0.6%
3	1.1%	0.4%
4	1.6%	0.7%
5	1.4%	0.5%
Mean $\pm$ observed range	1.38% $\pm$ 0.25%	0.54% $\pm$ 0.15%

Table 1. Representative results of selected quality assurance procedures before and after implementation of uncertainty-based assessment.

Procedure	Evaluated parameter	Variability before implementation	Variability after implementation	Expanded uncertainty after implementation, $k = 2$	Practical effect
Absorbed dose rate in a water phantom	Deviation from reference dose rate	$\pm 1.4\%$	$\pm 0.6\%$	1.1%	Improved repeatability of reference dosimetry
Reference measurement in a PMMA phantom	Corrected chamber reading	$\pm 1.2\%$	$\pm 0.5\%$	0.9%	Reduced day-to-day measurement variability
Percentage depth dose	PDD/PDG value at reference depth	$\pm 1.0\%$	$\pm 0.5\%$	0.8%	More stable assessment of beam quality
Tissue-phantom ratio for photon beams	TPR value	$\pm 0.9\%$	$\pm 0.4\%$	0.7%	Improved monitoring of photon beam quality
Flatness and symmetry of beam profiles	Profile parameters	$\pm 1.3\%$	$\pm 0.7\%$	1.0%	Better distinction between setup uncertainty and beam deviation
Physical wedge factor	Wedge transmission factor	$\pm 1.1\%$	$\pm 0.5\%$	0.8%	Improved reproducibility of accessory-related measurements
PMMA plate transmission factor	Transmission factor	$\pm 1.0\%$	$\pm 0.4\%$	0.7%	Improved control of auxiliary absorber measurements
Wood's alloy block transmission factor	Transmission factor	$\pm 1.5\%$	$\pm 0.7\%$	1.1%	Improved detection of block-related deviations
Long- and short-term accelerator stability	Output constancy	$\pm 1.6\%$	$\pm 0.6\%$	1.0%	Earlier identification of output drift
Therapeutic dosimeter stability	Corrected control-source reading	$\pm 1.2\%$	$\pm 0.5\%$	0.9%	Improved monitoring of dosimeter response stability

The expanded uncertainty of the absorbed dose rate measurement after implementation was estimated at 1.1% for $k = 2$. Therefore, deviations within this interval were interpreted as consistent with the metrological capability of the method, whereas deviations exceeding the uncertainty-based decision criterion prompted verification of the measurement setup, environmental correction factors, ionization chamber response, electrometer reading stability, and accelerator output.

This example shows that uncertainty analysis acted not only as a reporting tool but also as a practical method for improving measurement stability. By identifying the dominant components of the uncertainty budget and standardizing the measurement procedure, the variability of the absorbed dose rate measurement was reduced and the interpretation of routine quality control results became more objective.

A similar effect was observed for relative dosimetric procedures, including wedge factor measurements, PMMA plate transmission measurements, and Wood's alloy block transmission measurements. In these procedures, uncertainty analysis helped identify the dominant sources of variability, such as repeatability of electrometer readings, reproducibility of phantom or accessory positioning, and consistency of environmental corrections. As a result, the measurement process became more standardized and less dependent on operator-specific factors.

The implementation of uncertainty budgets also improved the interpretation of long- and short-term stability tests of accelerator output. Instead of evaluating each result only against a fixed tolerance limit, the result was assessed in relation to the metrological capability of the method. This approach allowed early identification of trends that were still within clinical tolerance limits but exceeded the expected measurement variability. Such cases were treated as warning signals and prompted additional verification before clinically significant deviations occurred.

Overall, the uncertainty-based quality assurance system reduced observed measurement variability in the analyzed procedures and improved the consistency of result interpretation. The results confirmed that uncertainty analysis was not only a formal requirement of the accredited system but also a practical tool for monitoring measurement stability, detecting early deviations, and supporting preventive quality assurance in radiotherapy dosimetry.

Conclusions

These findings confirm that accreditation-based metrological frameworks significantly improve the robustness of dosimetric procedures and reduce the risk of clinically significant errors in radiotherapy. Accreditation, first obtained in 2013 and renewed in subsequent years, was important not only formally but also because it introduced lasting changes in the operation of the Medical Physics Department. The measurement system became better organized, result stability increased, and measurement variability decreased, directly improving clinical safety and facilitating a preventive rather than reactive approach.

Accreditation confirmed that the measurements met the highest quality standards and that the results were repeatable, reproducible, and metrologically consistent. The most significant effect was that accreditation became a permanent working standard and an integral element of the Department's organizational culture, functioning without the need for periodic reminders of its importance.

Preparation for accreditation to the PN-EN ISO/IEC 17025 standard required substantial commitment, technical precision, and organizational consistency. It was a project that integrated expertise in medical physics, metrology, quality management, and teamwork. Regardless of the duration of subsequent accreditation extensions, from today's perspective this was one of the most important developmental decisions for the Department—a decision that increased patient safety and measurement reliability and significantly reduced the likelihood of undesirable dosimetric events, including issues related to the dosimetric specification of radiotherapy equipment and auxiliary devices^{16,21}.

Implementation of an accredited quality assurance system in accordance with PN-EN ISO/IEC 17025 resulted in improved measurement consistency, reduced variability, and enhanced clinical safety.

Integration of measurement uncertainty analysis enabled quantitative assessment of measurement reliability and supported early detection of deviations in accelerator performance.

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